BNL, October 8th, 2012

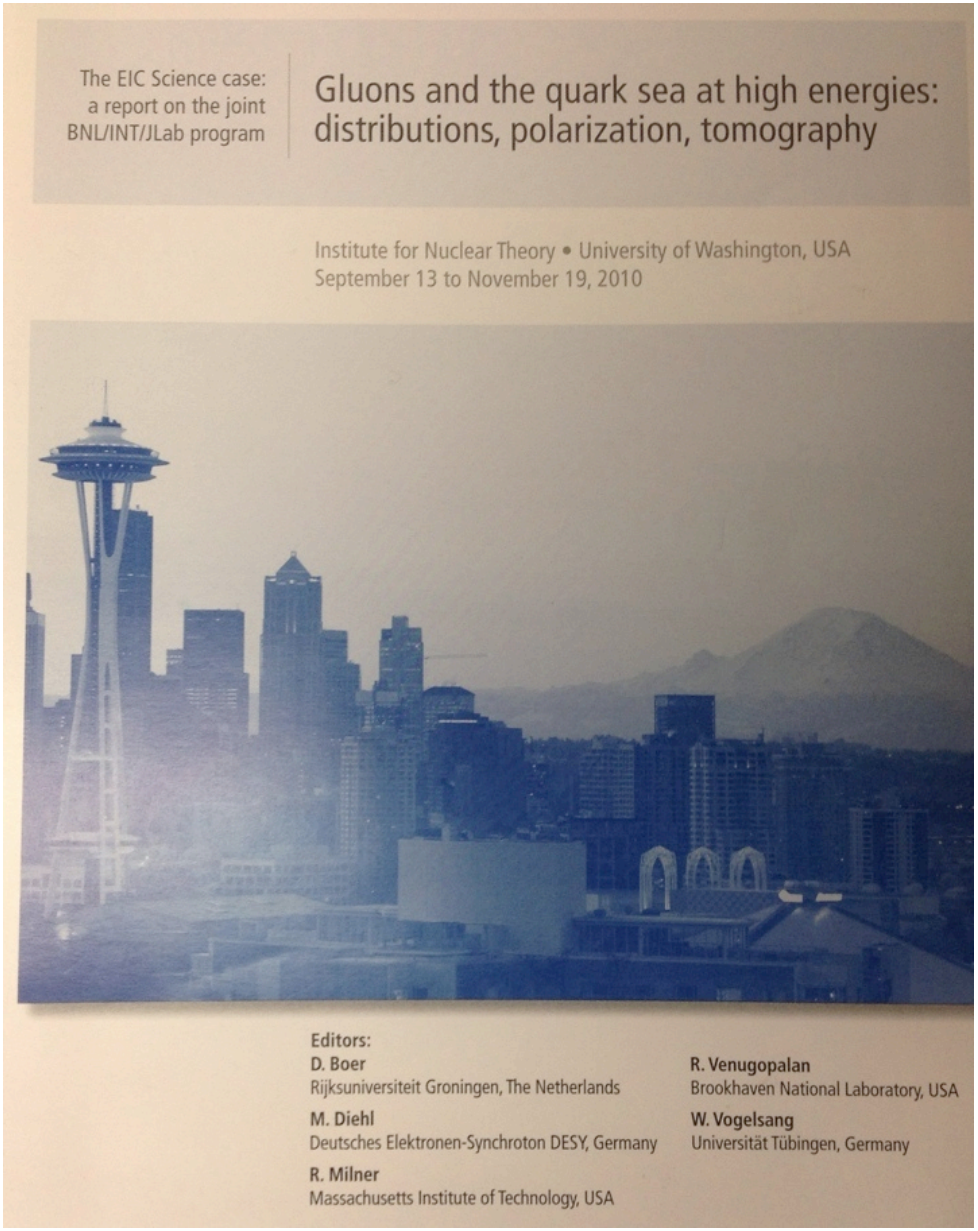
A Quick Tour of the EIC Physics Case

Marco Stratmann

BROOKHAVEN NATIONAL LABORATORY

marco@bnl.gov

this talks can only present some highlights of the EIC program



in the absence of the EIC white paper,
I refer to the **500+ pages** INT report
arXiv:1108.1713

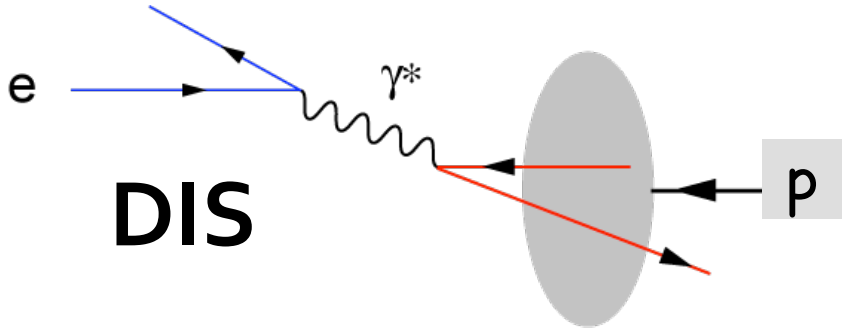
presented results are
mainly due to the efforts of
the EIC task force at BNL
and other supporters of an EIC

1

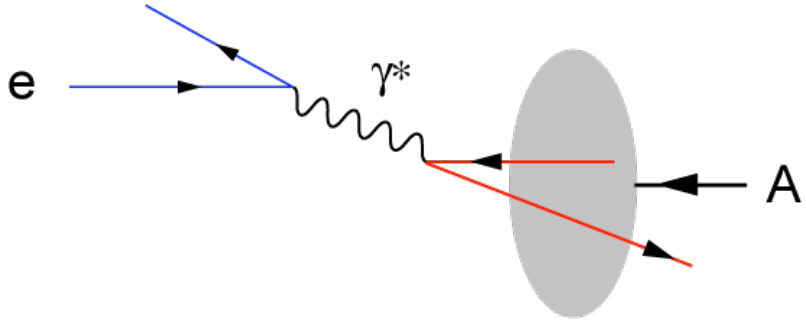
inclusive deep-inelastic scattering in ep and eA

what to measure

bread and butter probe at an electron-ion collider



DIS



need to measure only the **scattered electron** (its **energy** and **angle**)

- fully determines **two relevant kinematical variables**

  a 3rd variable (**inelasticity y**) is related to x, Q^2 through the available c.m.s. energy

Q^2 : virtuality of exchanged photon

x : momentum fraction of probed parton

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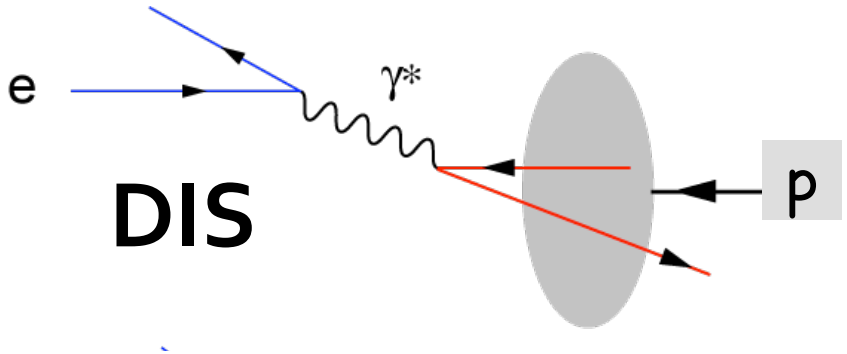

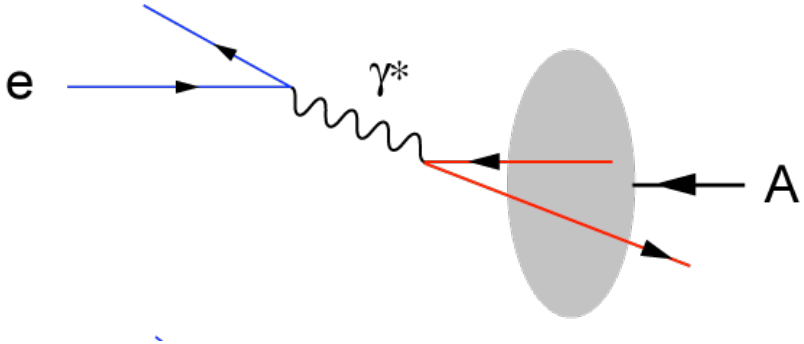

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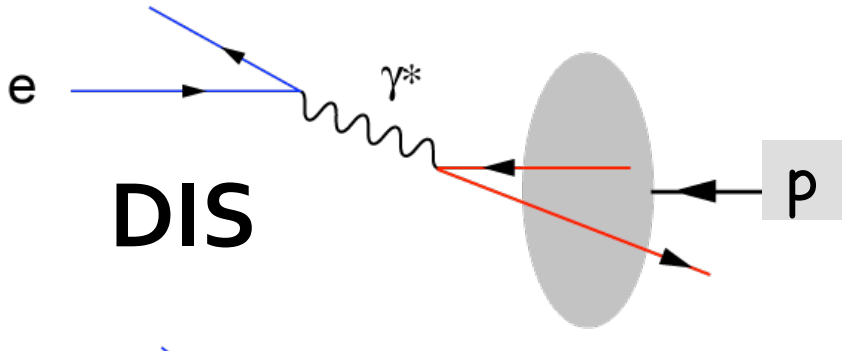

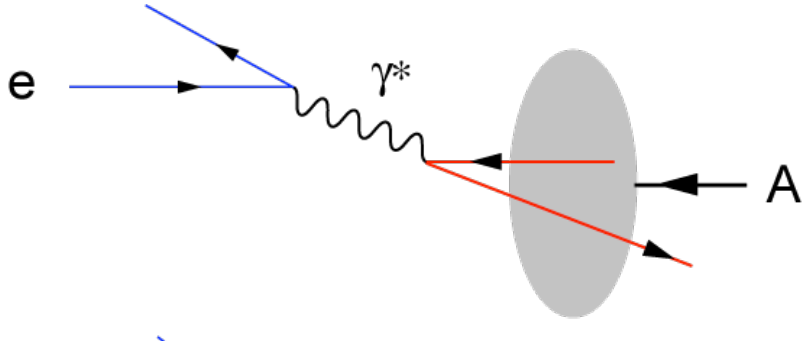

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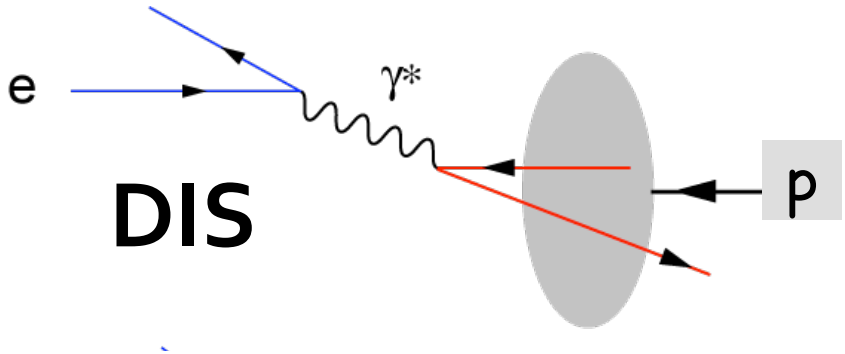

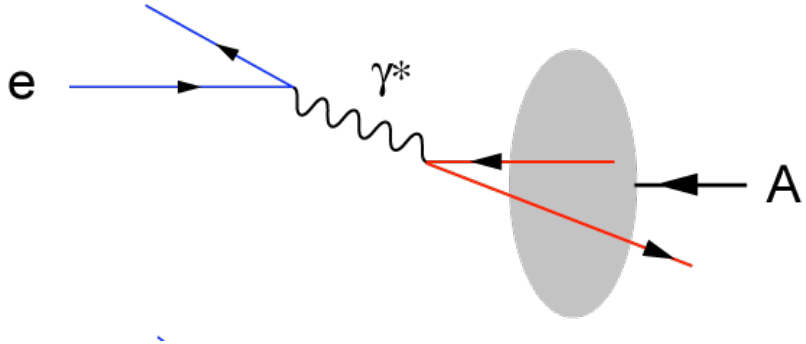

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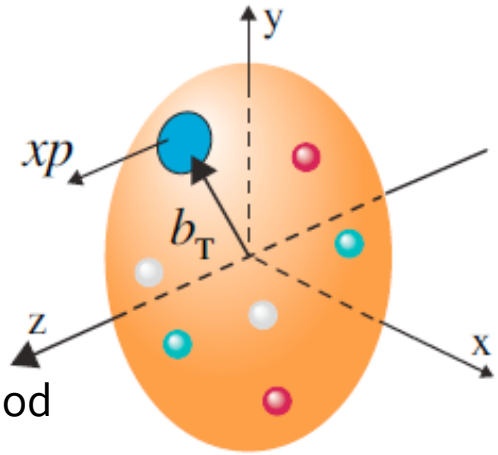
- ☐ need to measure also the polarization (and luminosity) very well

why is this interesting and what can we learn?

DIS measurements are *the* **classic tool** to study the partonic structure of nucleons (nuclei):



- ☑ distribution of partons in longitudinal momentum x
- ☑ **gluon density** from studying Q^2 dependence for fixed x
- ☑ theory tools and higher order QCD corrections well understood
- ☐ not so good for separation of quark flavors
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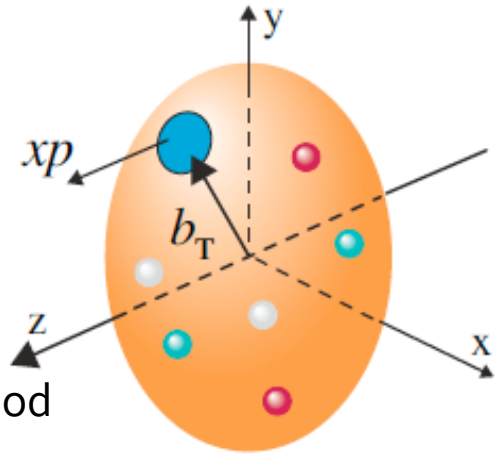

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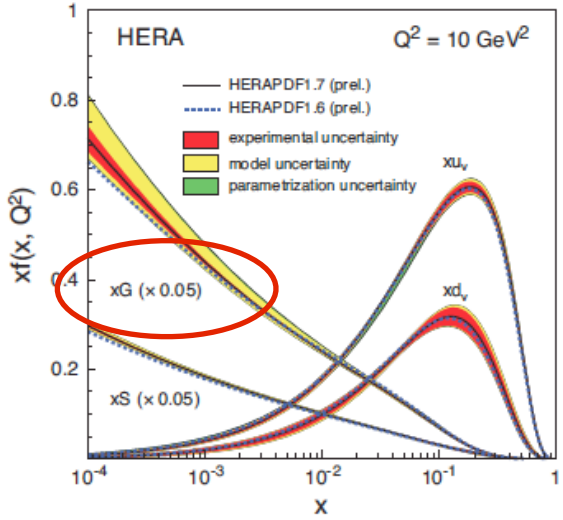

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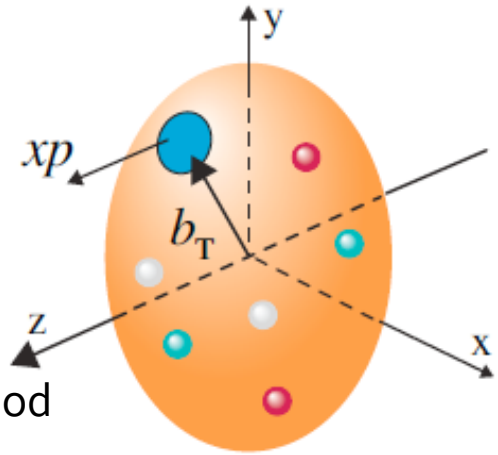

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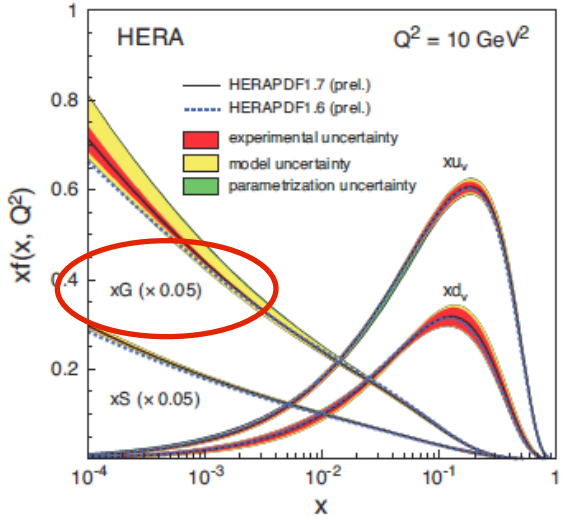

- HERA has studied unpolarized ep scattering in great detail
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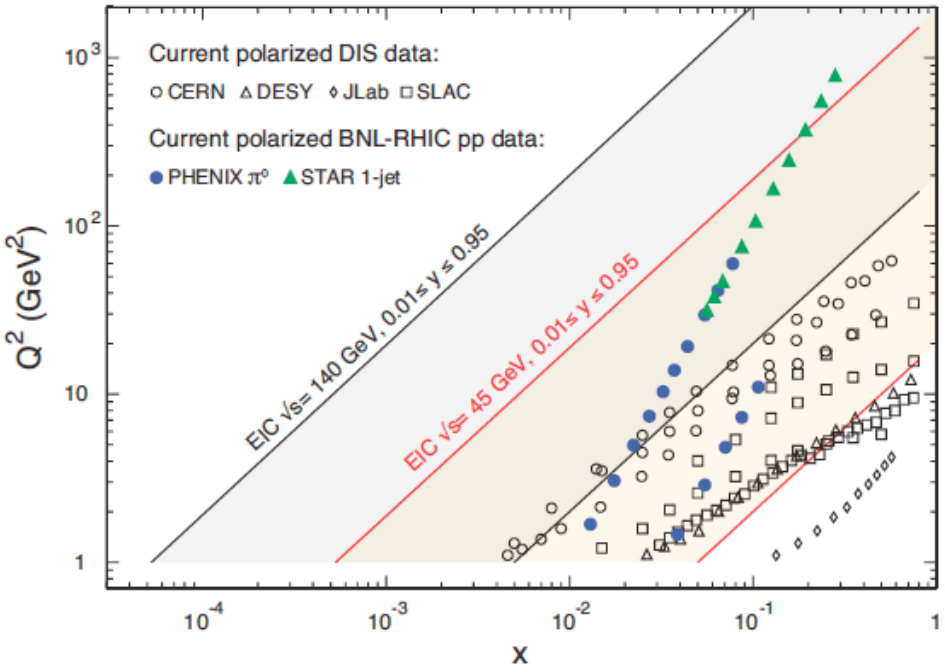
- current data for **polarized ep and eA DIS** cover only a very restricted x,Q^2 range (**no collider experiments so far**)

extension of x, Q^2 coverage with an EIC

polarized ep scattering



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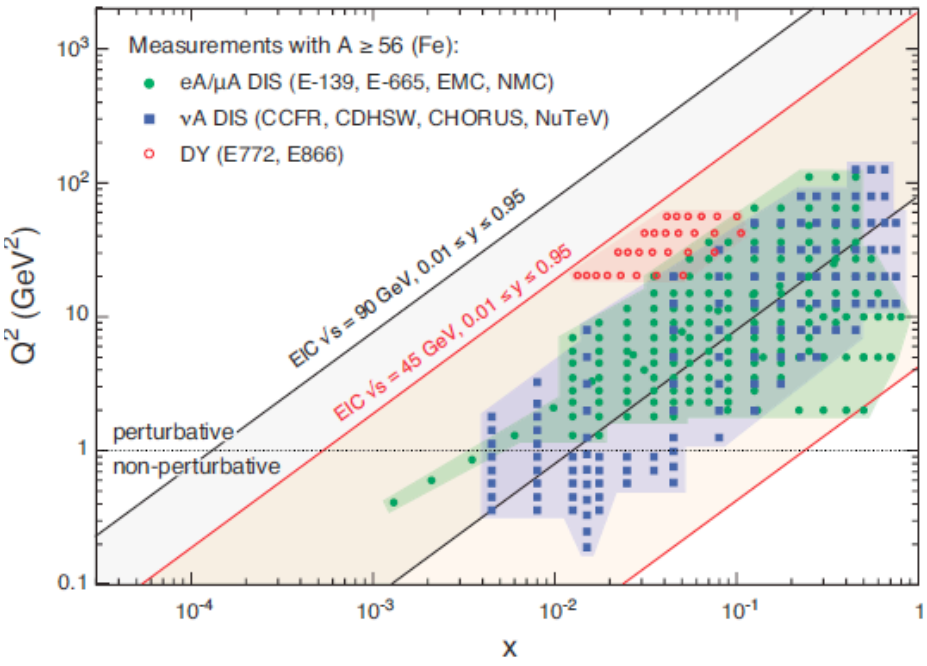

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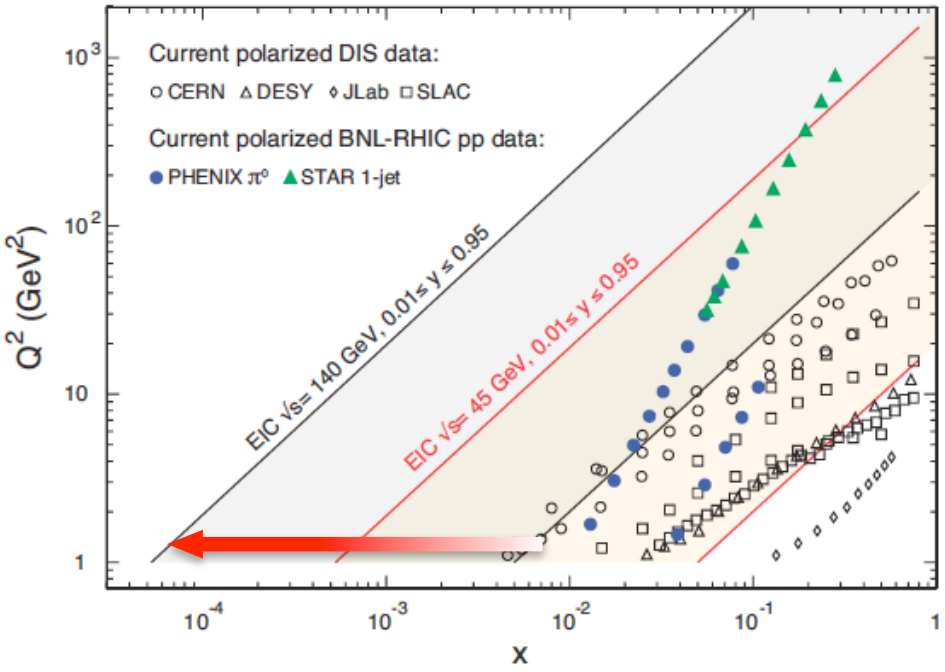

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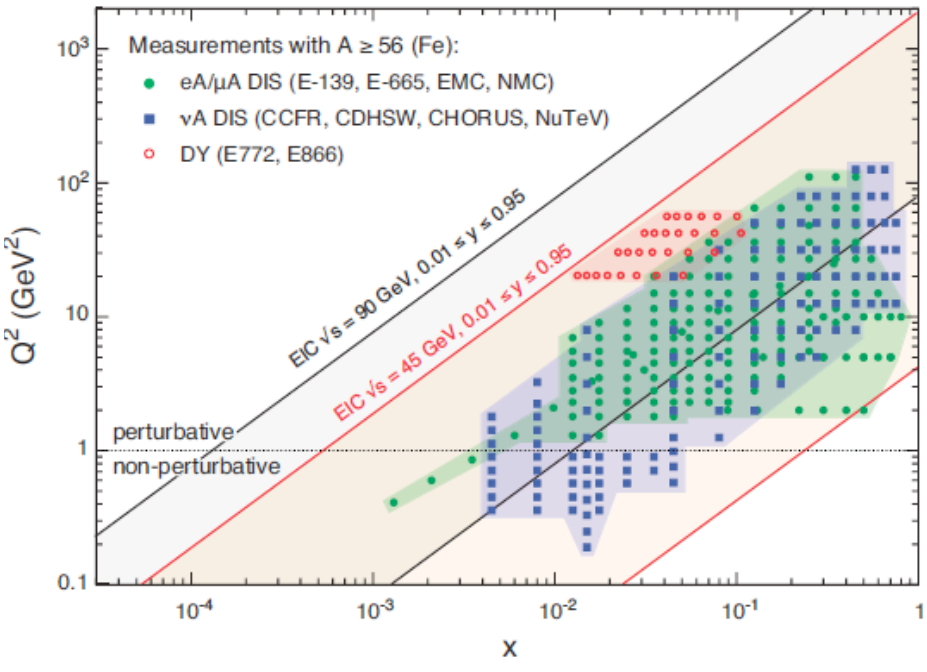

- **gain two decades in x** -> get into the region where gluons and sea quarks dominate

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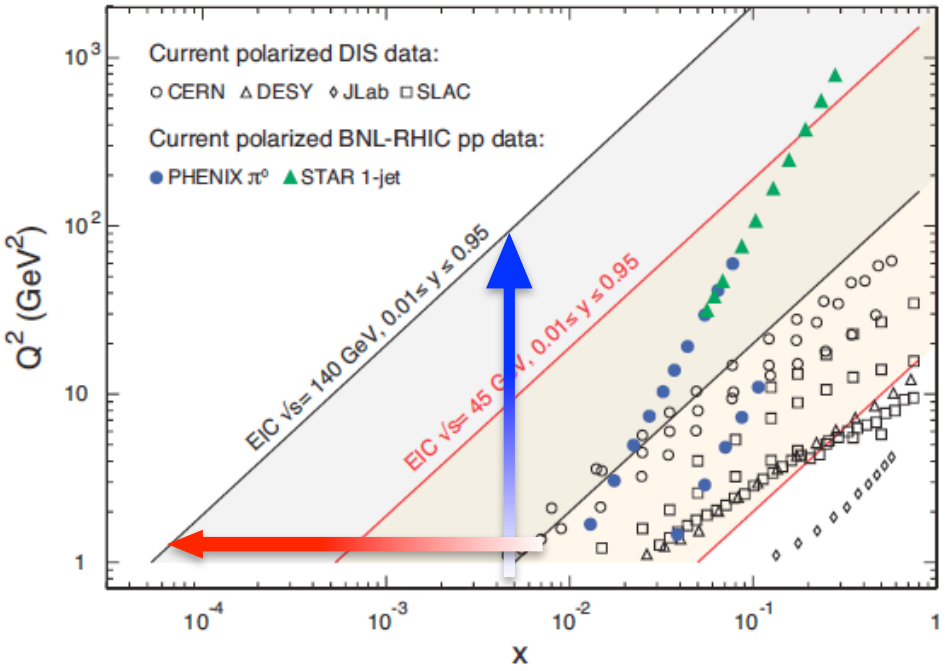

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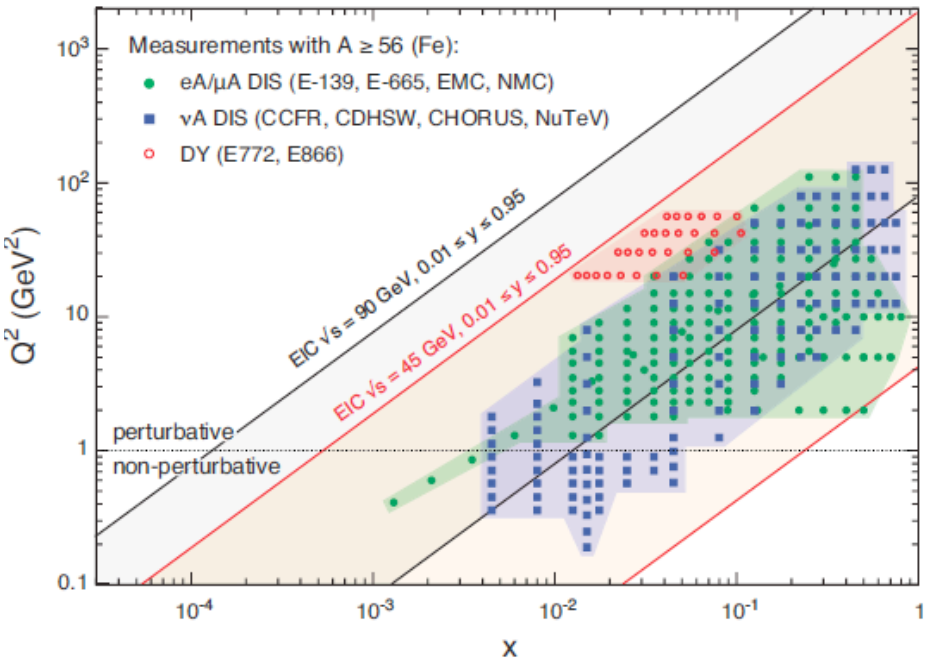

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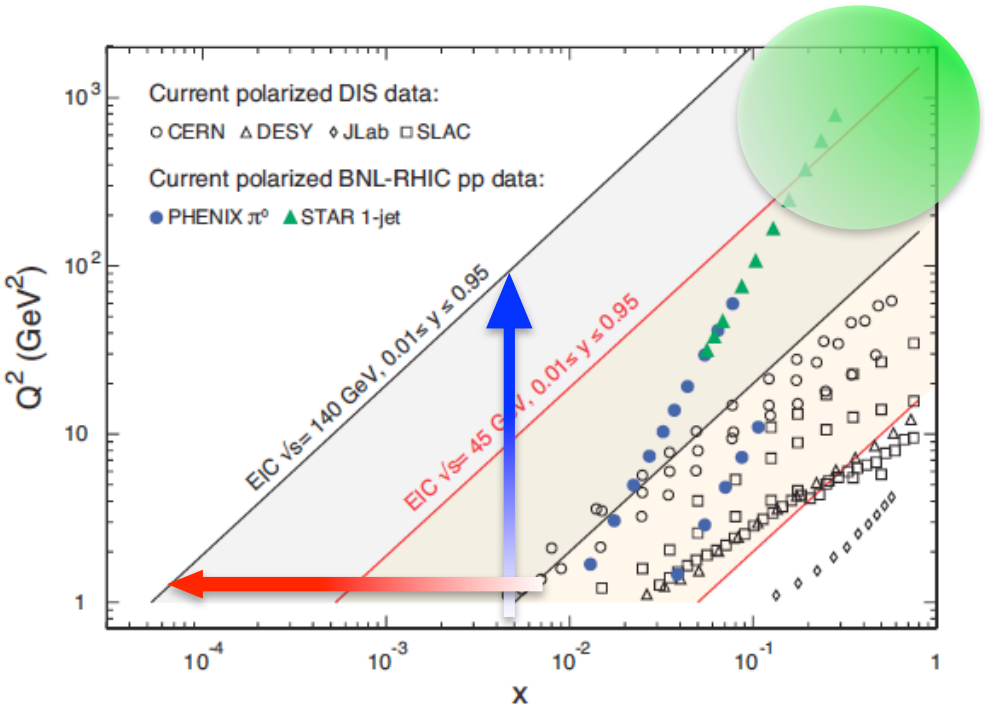

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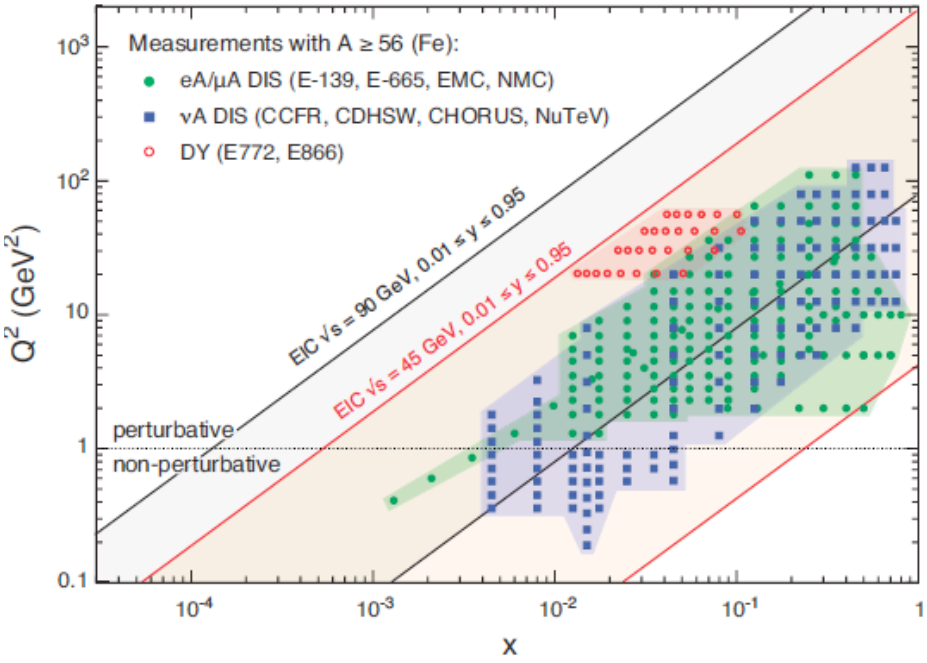

- **gain two decades in x** -> get into the region where gluons and sea quarks dominate
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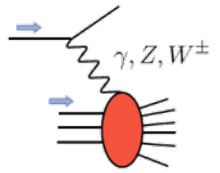
- **can reach large Q^2** (at medium-to-large x) -> access to electroweak effects



what can be achieved: spin structure

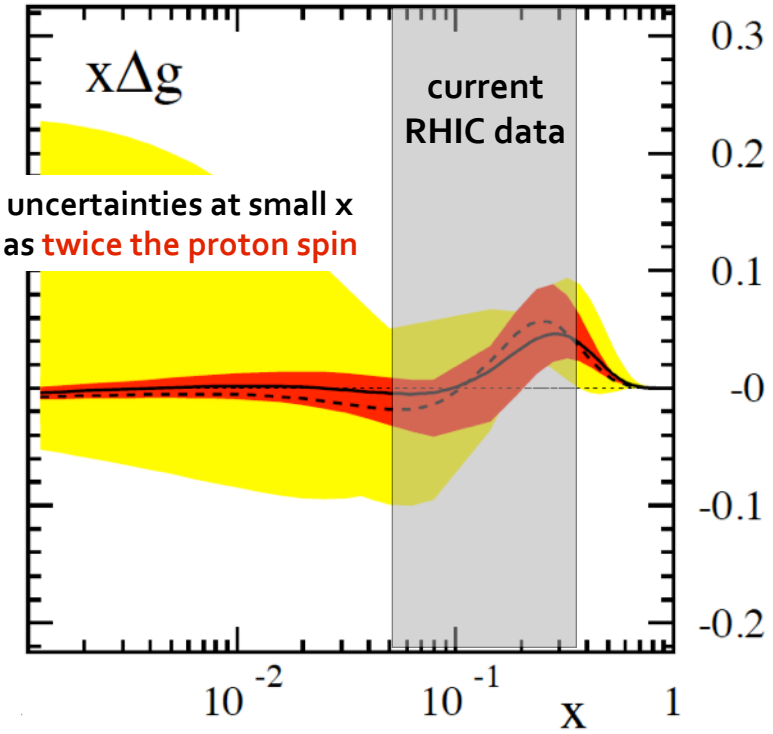
- RHIC will determine $\Delta g(x,Q^2)$ down to $x \simeq$ few $\times 10^{-2}$

  but need access down to few $\times 10^{-4}$ to close chapter on spin

recall:

$$\Delta f(x) \equiv f_{\rightarrow}^{\rightarrow}(x) - f_{\leftarrow}^{\rightarrow}(x)$$

- an EIC can do just that …



present uncertainties at small x as large as twice the proton spin

based on global QCD analyses with and without realistic EIC pseudo data

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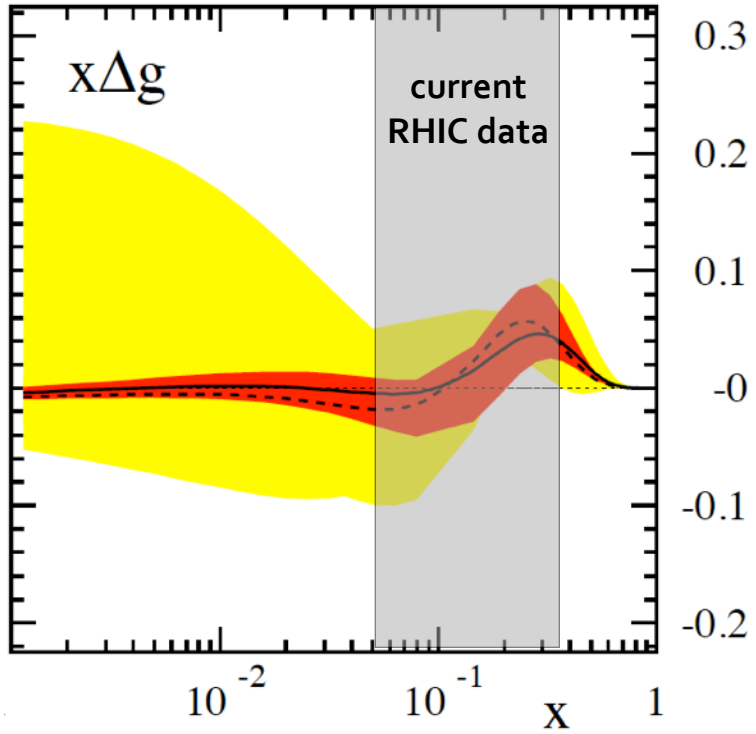

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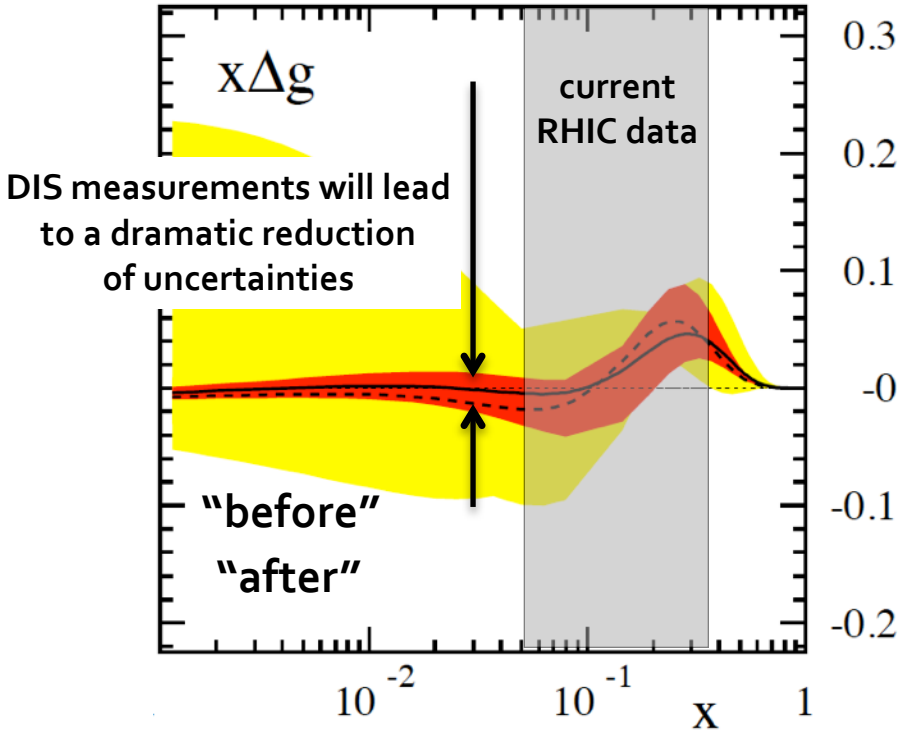

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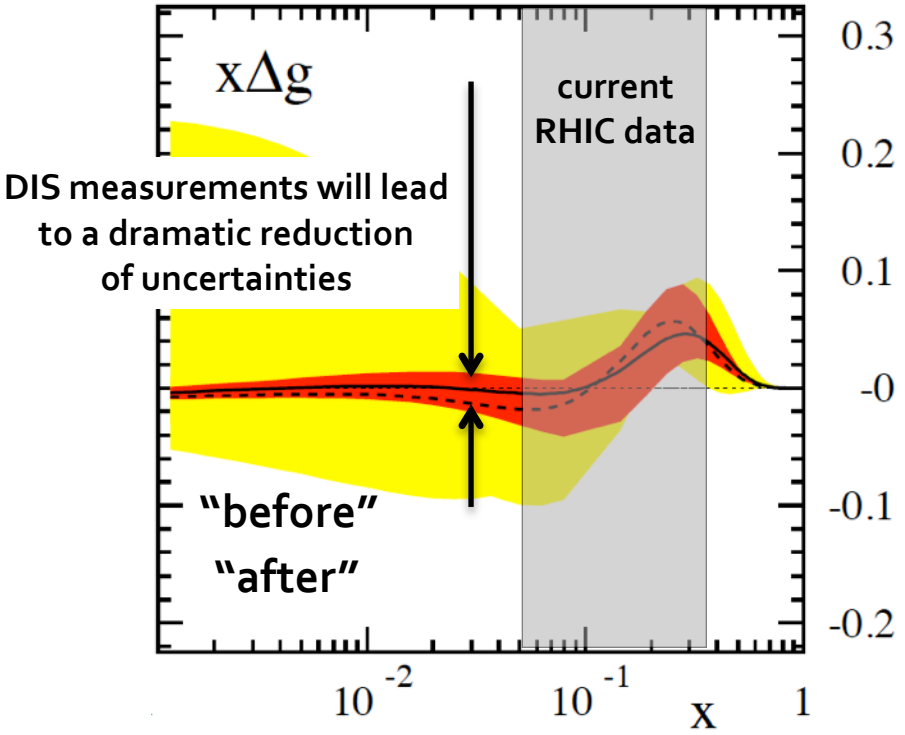

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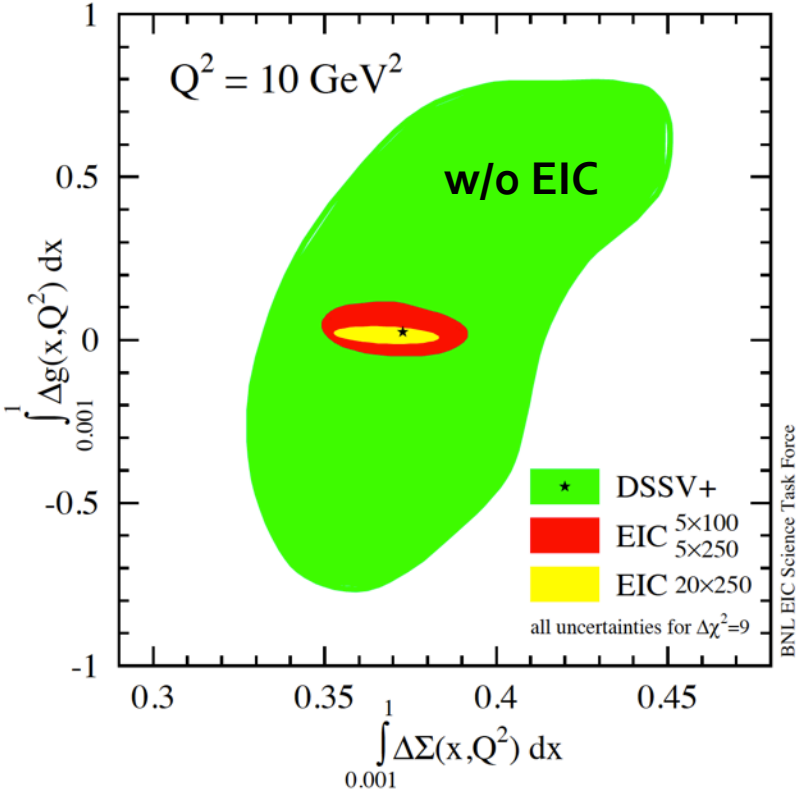
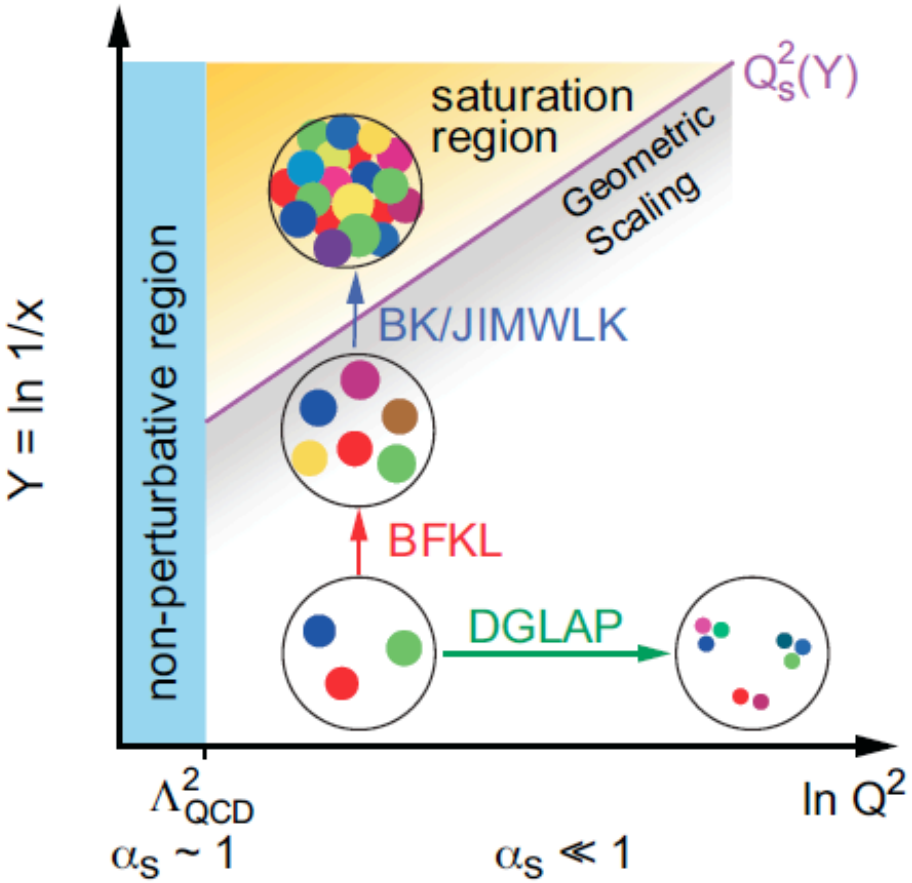


crucial impact on our understanding of decomposition of proton spin

what can be achieved: nuclear PDFs

goals:

- map the momentum distribution of sea quarks and gluons down to small x
- gather unambiguous evidence for non-linear QCD dynamics (aka **saturation**)



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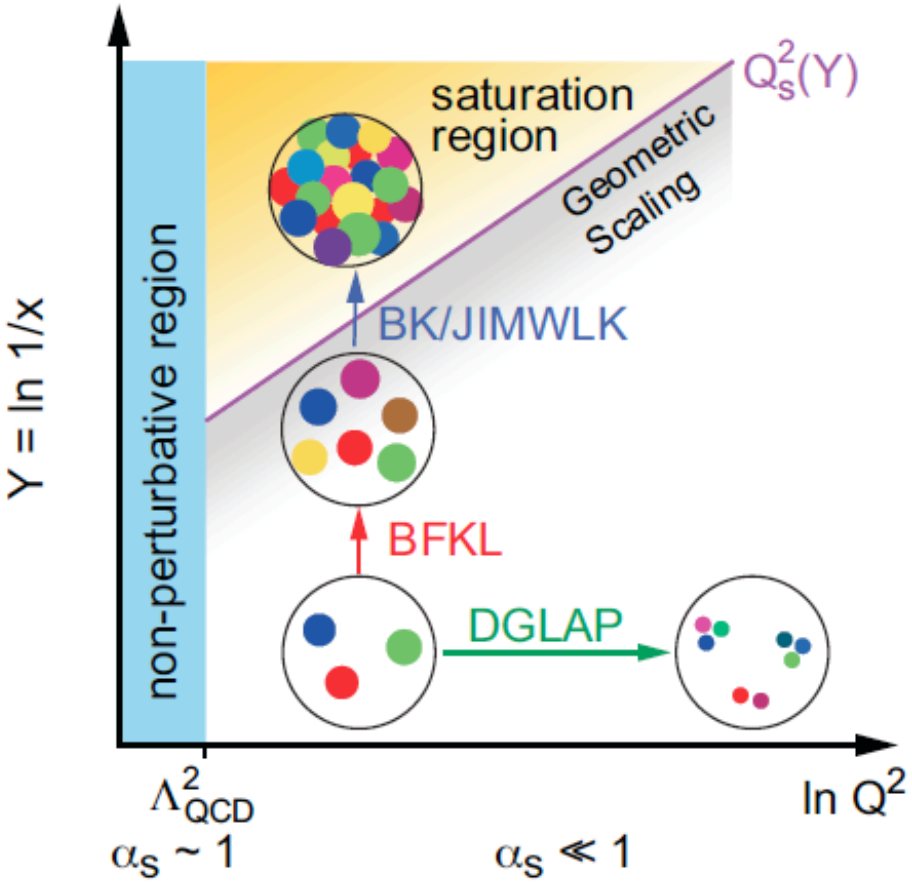

key advantage of eA DIS over ep DIS

amplification of non-linear effects by nuclear "oomph factor"

$$Q_s^2(x, A) \sim \left(\frac{A}{x}\right)^{1/3}$$

expect to see saturation in eA at 100-200 × higher values of x than in ep

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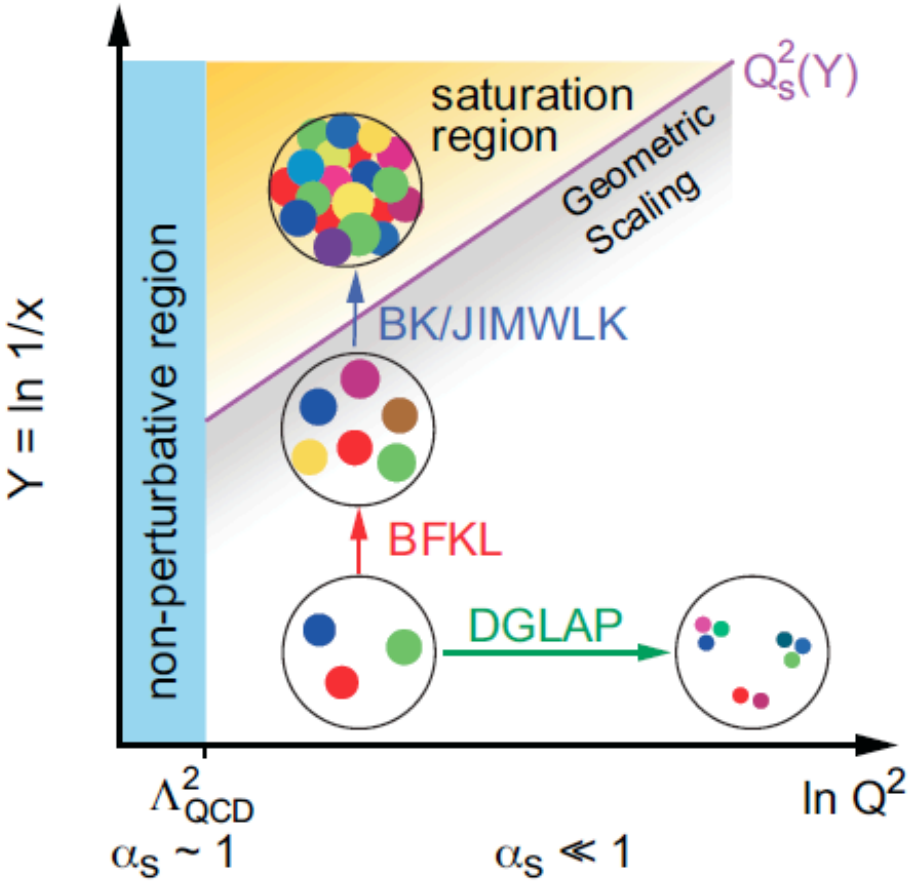

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- presence of (large enough) **saturation scale Q_s** allows one to perform quant. calculations in well-defined framework ("CGC")

- expect **"physics at high gluon density"** to be universal; can verify this at an EIC !

what can be achieved: nuclear PDFs

particularly suited inclusive observable: DIS structure function $F_L(x,Q^2)$ unmeasured so far

- extraction of F_L needs

  "Rosenbluth separation"

  measurements at fixed x,Q^2 for different y (i.e., S)

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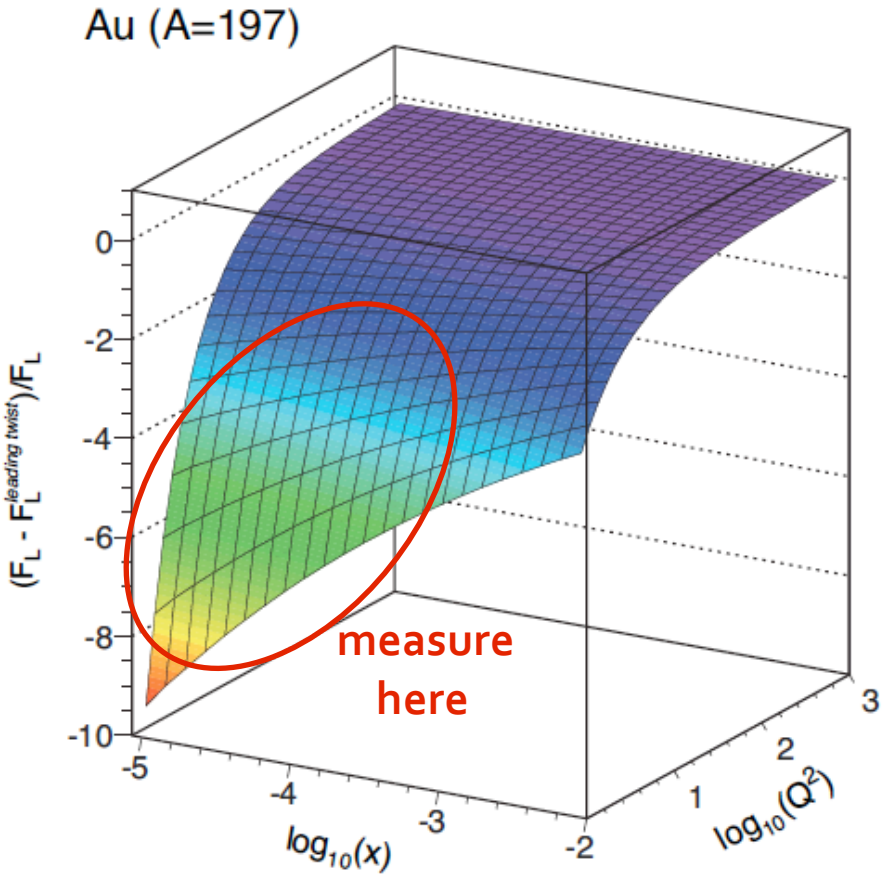

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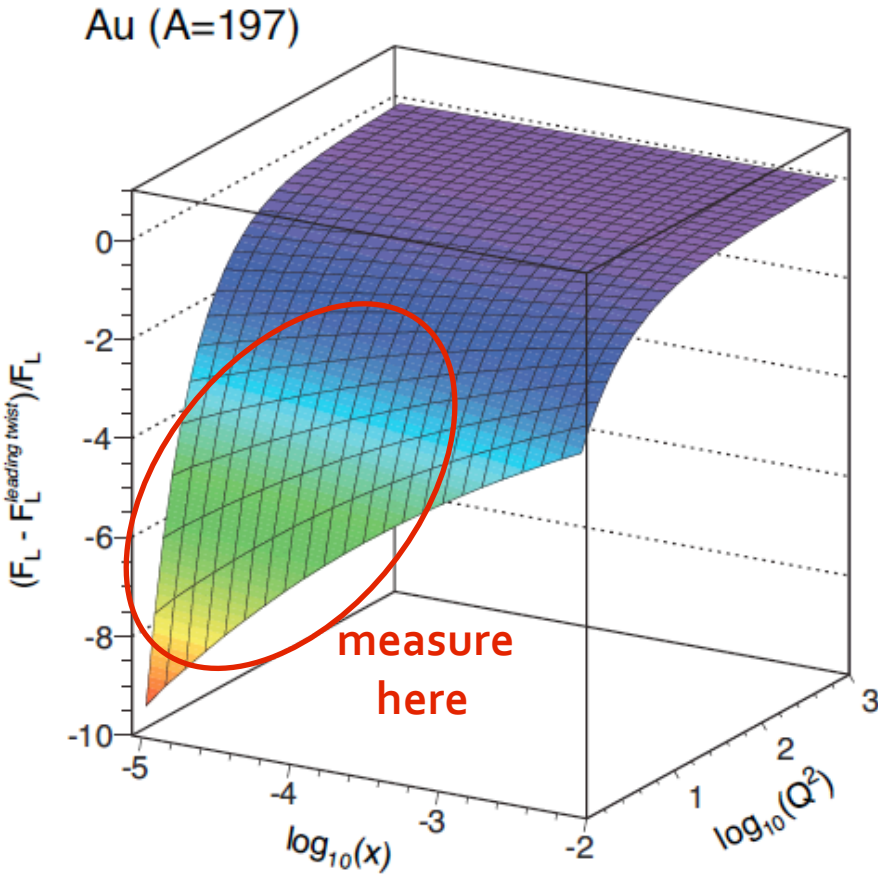

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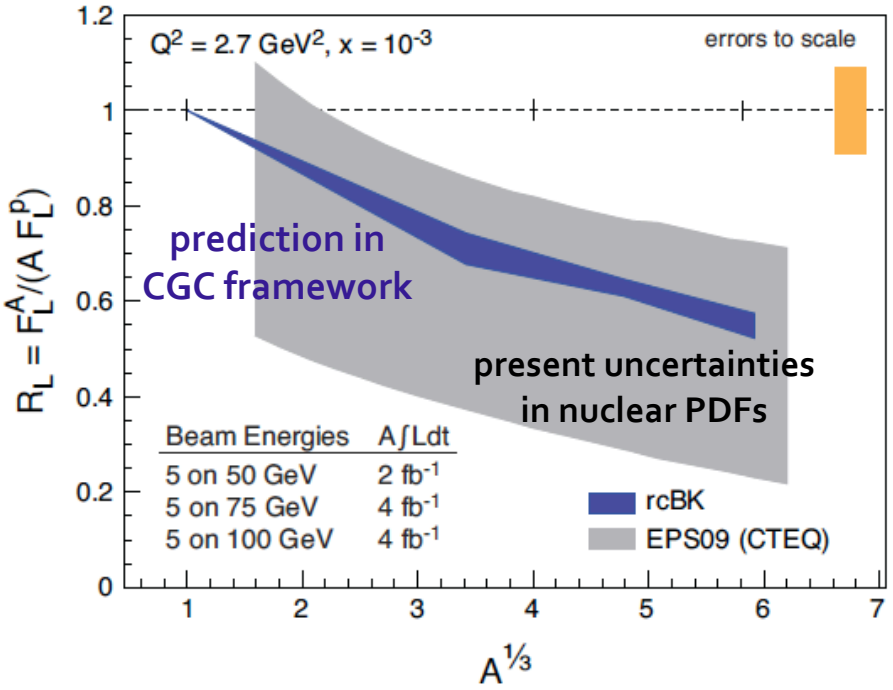
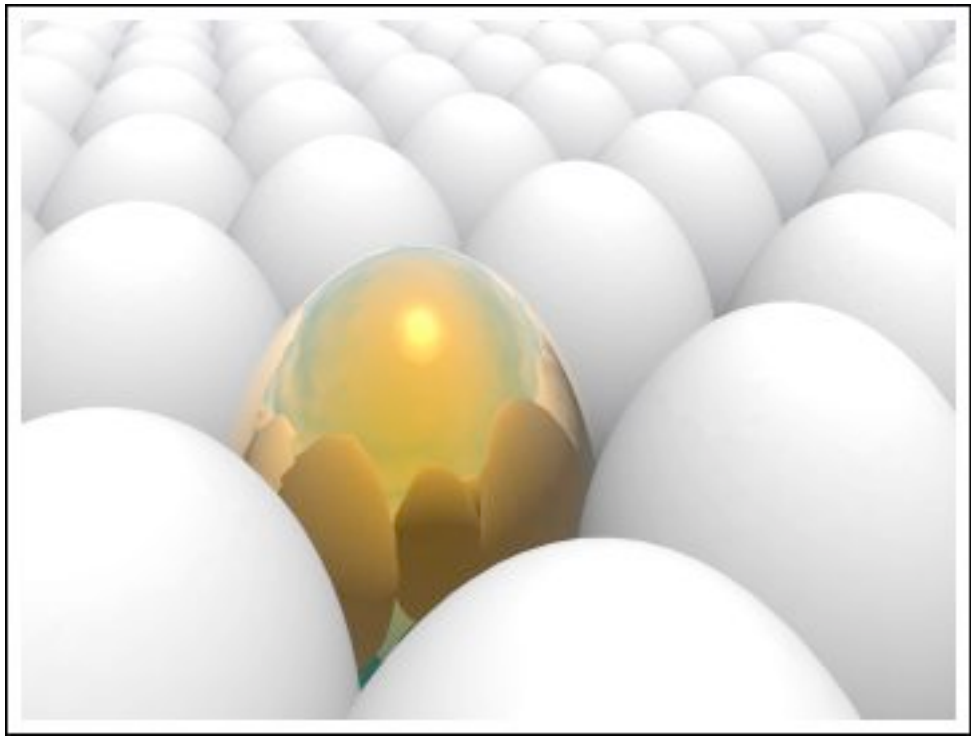
- can be done:



combined analysis with other observables can reveal presence of non-linear effects



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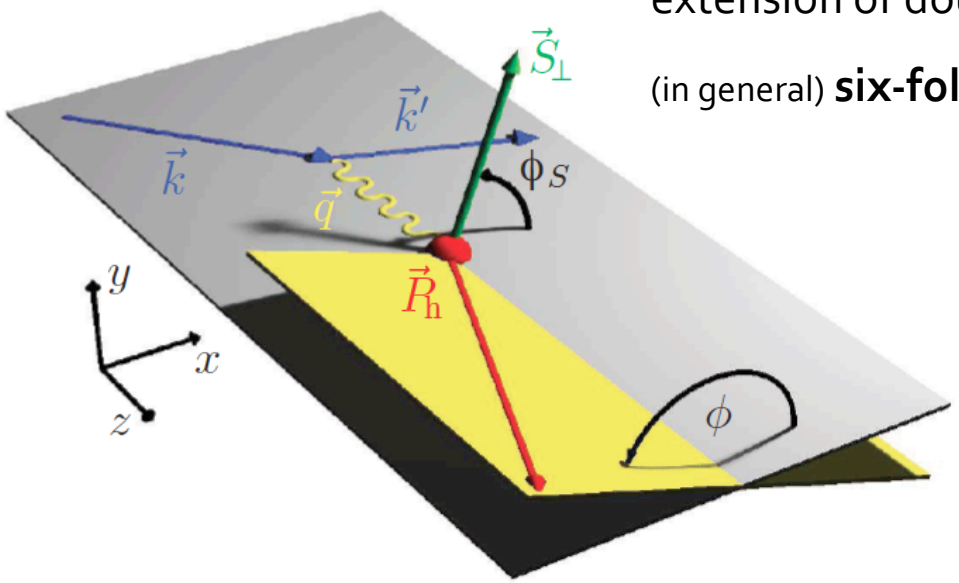
semi-inclusive probes in ep and eA

what to measure and why



extension of double-differential DIS cross section to a

(in general) **six-fold diff. cross section** $\dfrac{d\sigma}{dx\, dQ^2\, dz\, d\phi_S\, d\phi_h\, dp_T^h}$

z: energy fraction of observed hadron

p_T^h: its transverse momentum

ϕ: azimuthal angle of hadron

ϕ_S: azimuthal angle of spin vector

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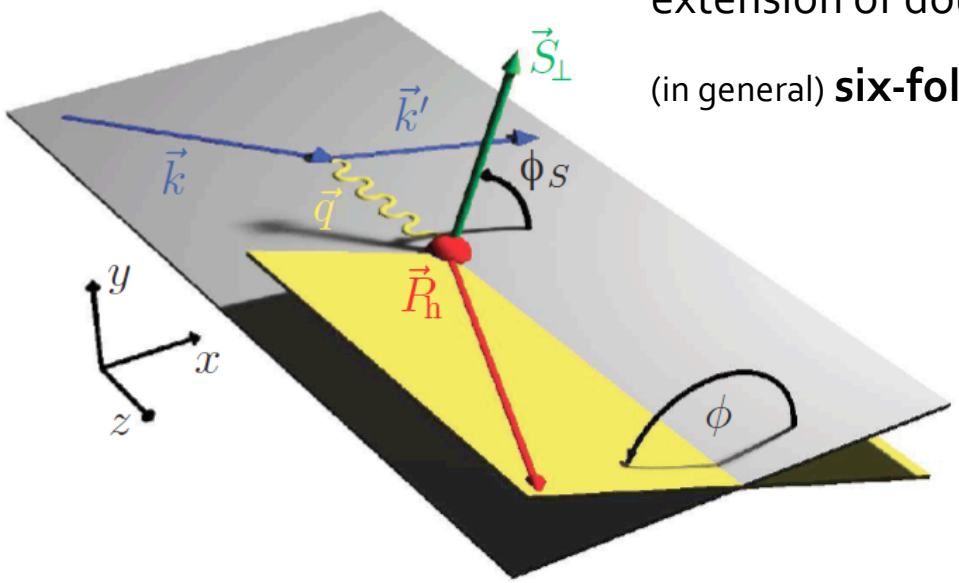

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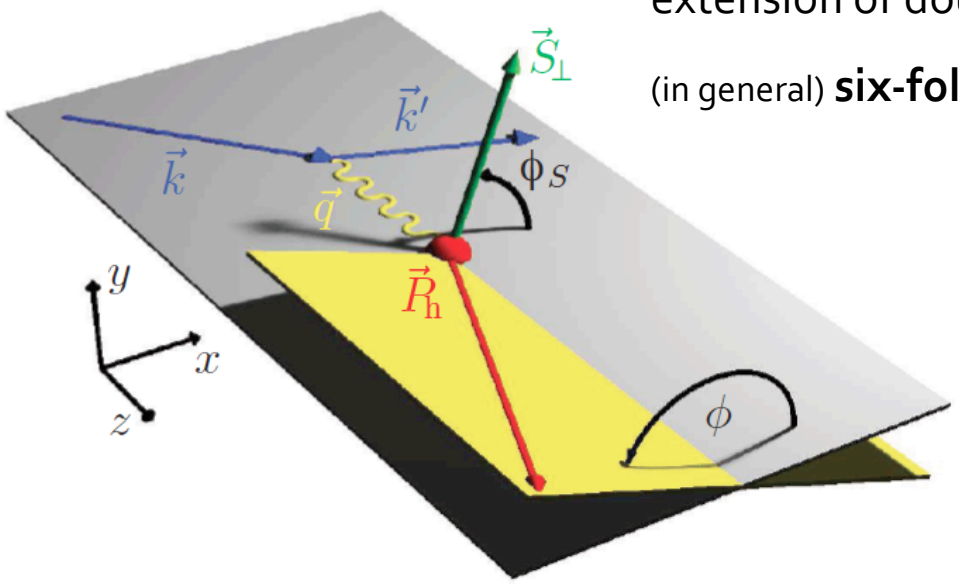

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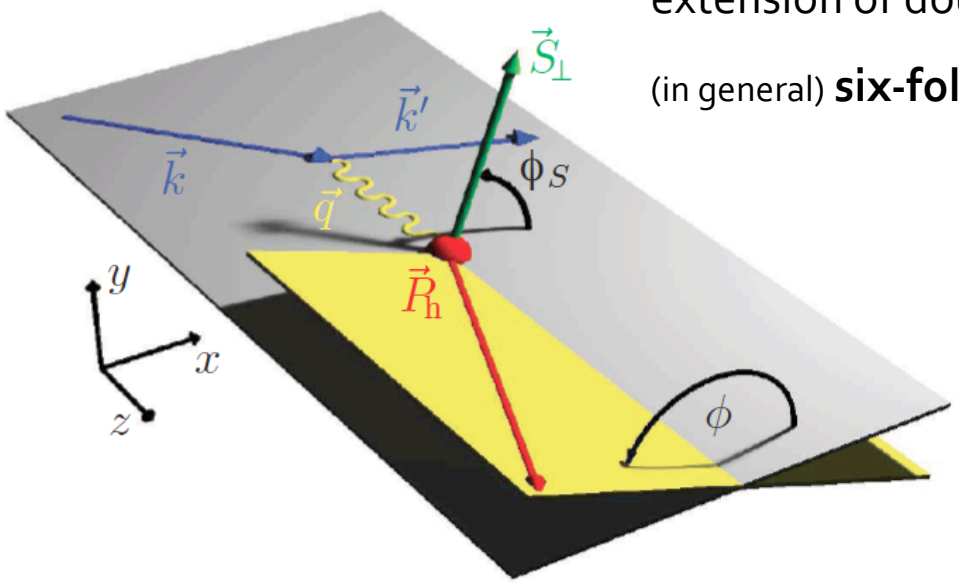
- **azimuthal modulations** lead to transverse momentum dependent PDFs (TMDs)

what to measure and why



extension of double-differential DIS cross section to a

(in general) **six-fold diff. cross section** $\dfrac{d\sigma}{dx\, dQ^2\, dz\, d\phi_S\, d\phi_h\, dp_T^h}$

z: energy fraction of observed hadron

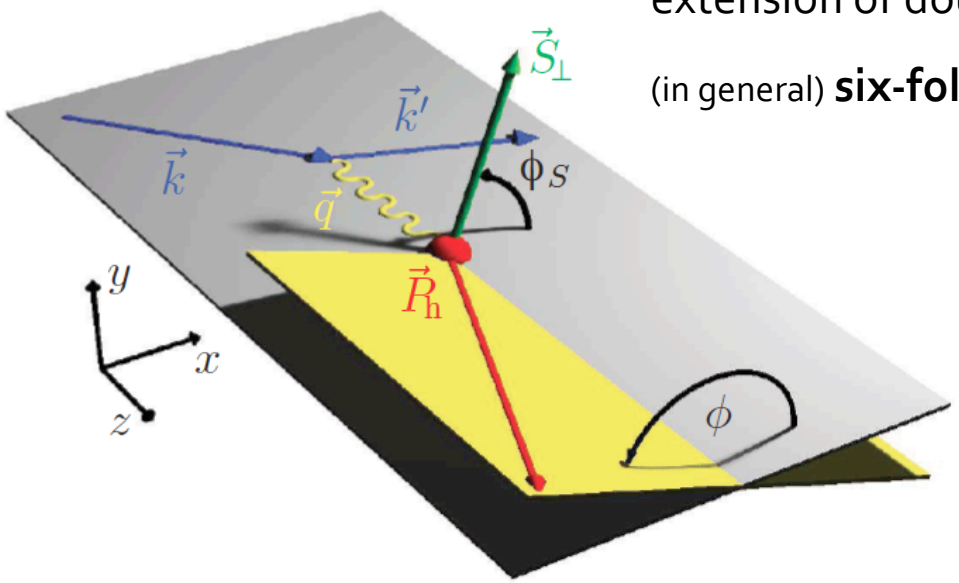
p_T^h: its transverse momentum

ϕ: azimuthal angle of hadron

ϕ_S: azimuthal angle of spin vector

- **p_T and ϕ integrated cross section** is simplest but versatile SIDIS observable
  can be used for flavor separation (needs π's and K's) and determinations of fragmentation functions
- **azimuthal modulations** lead to transverse momentum dependent PDFs (TMDs)
- **hadron-hadron correlations** in eA give clean access to saturation physics

what to measure and why



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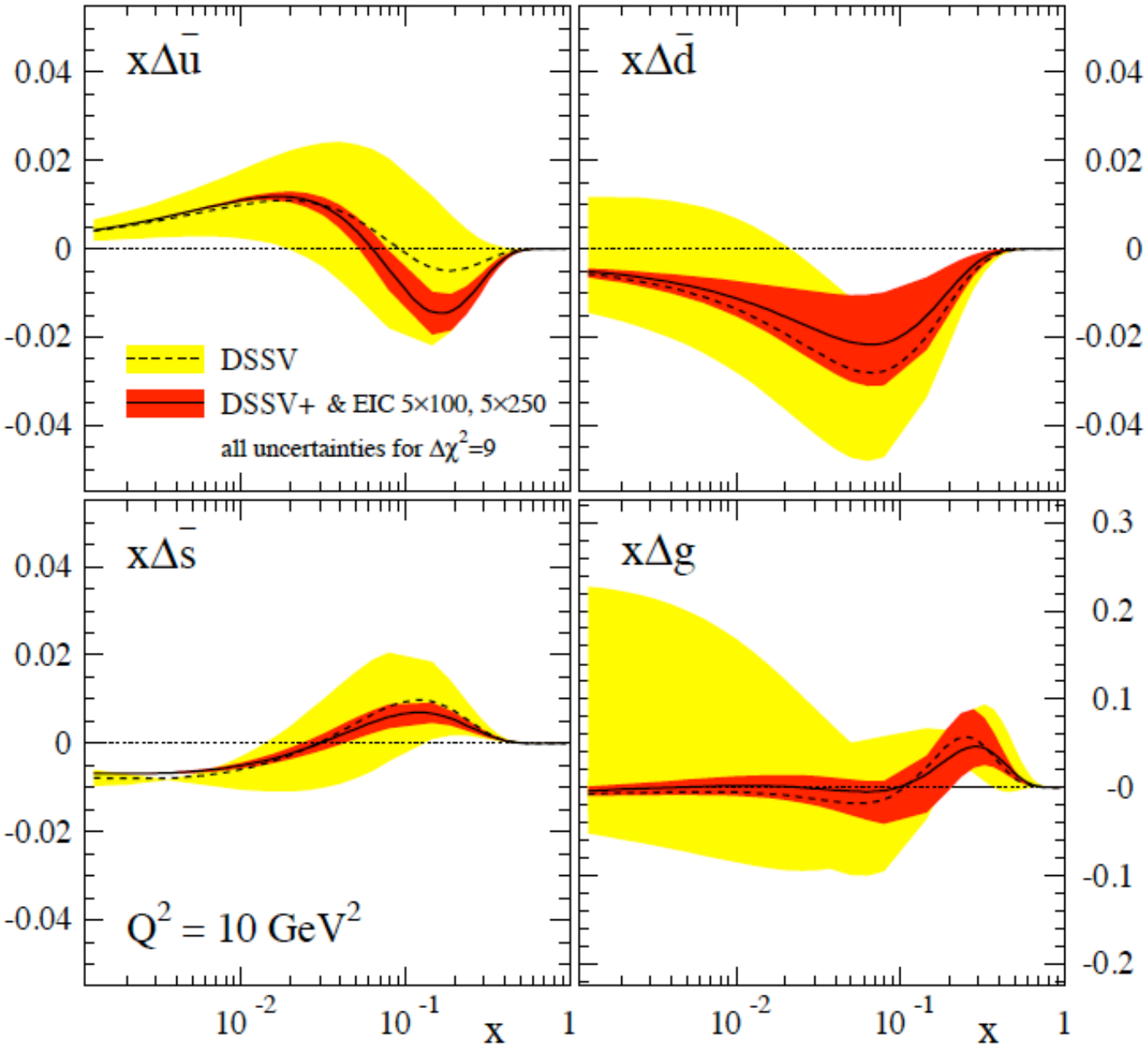
all SIDIS measurements require good particle ID in broad kinematic regime

1st example: flavor separation for helicity PDFs



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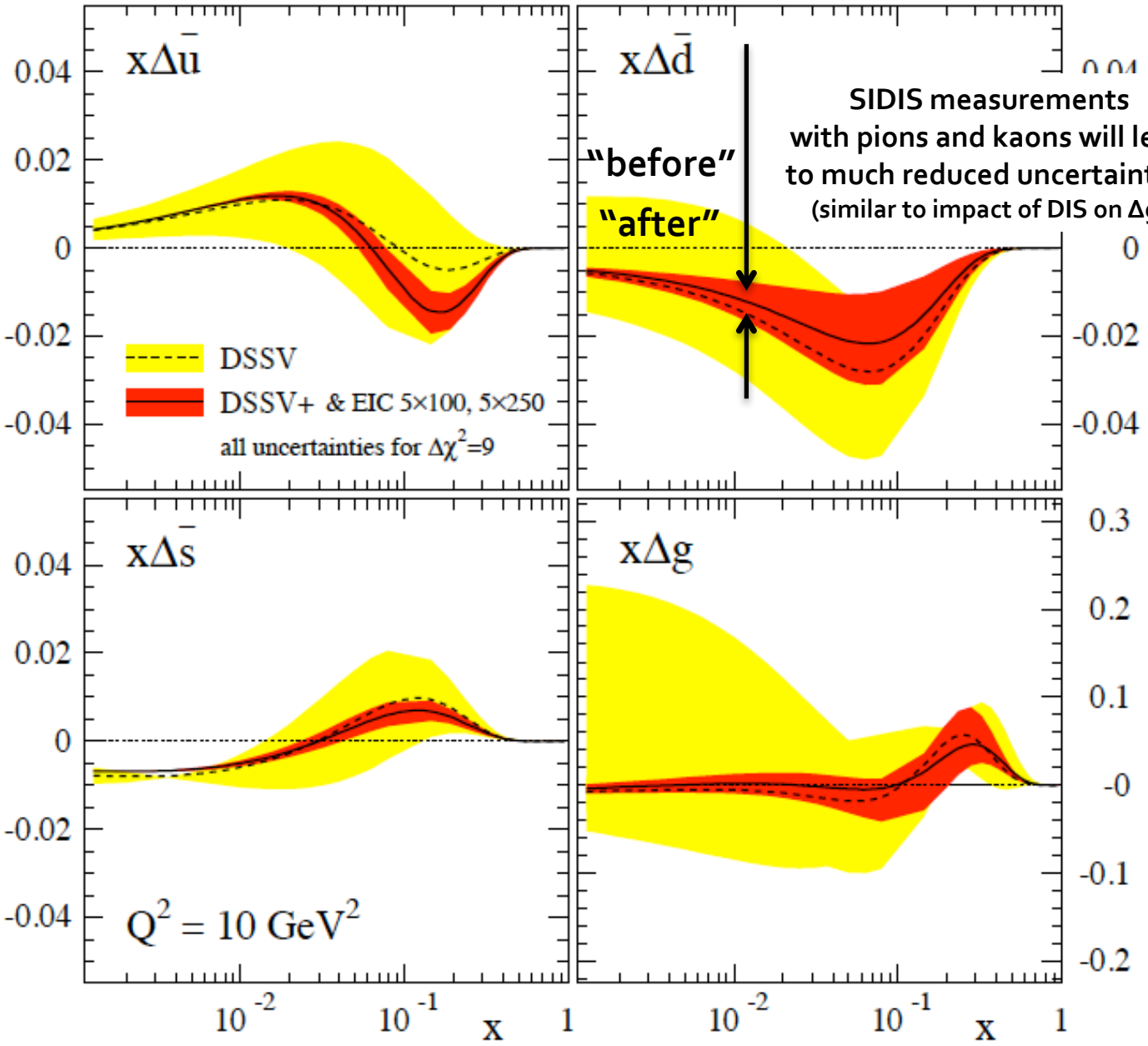

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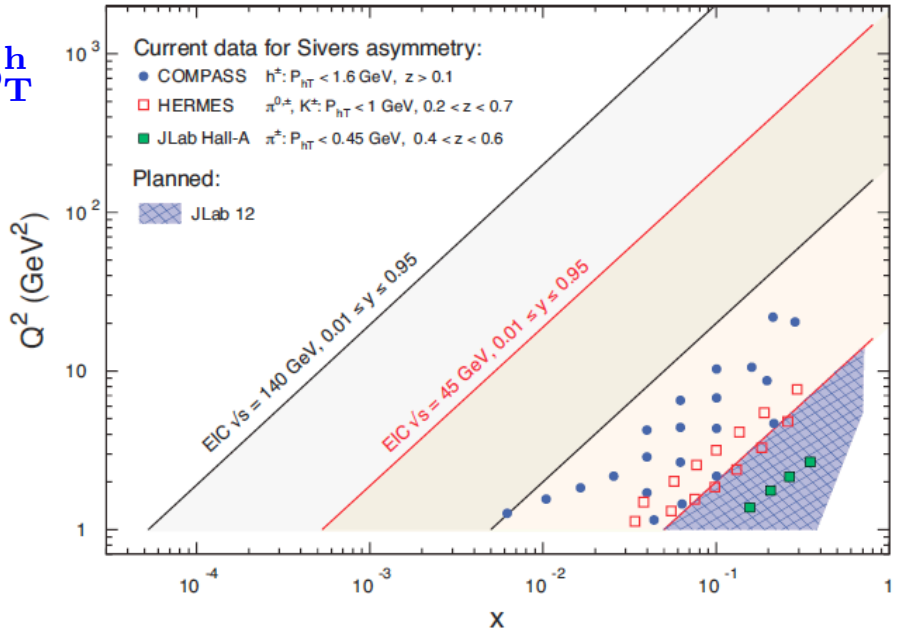

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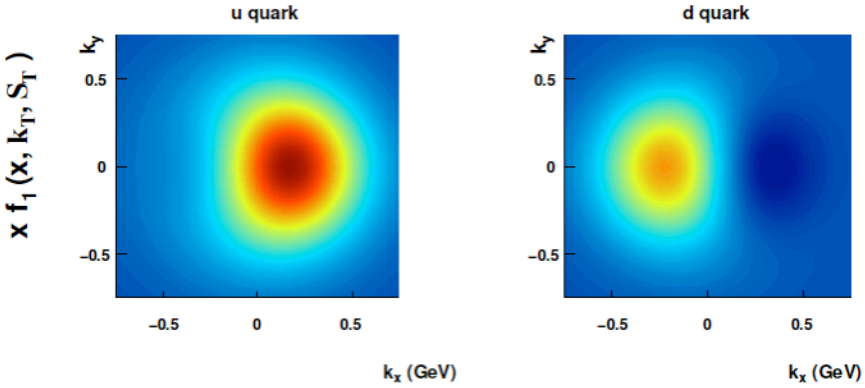

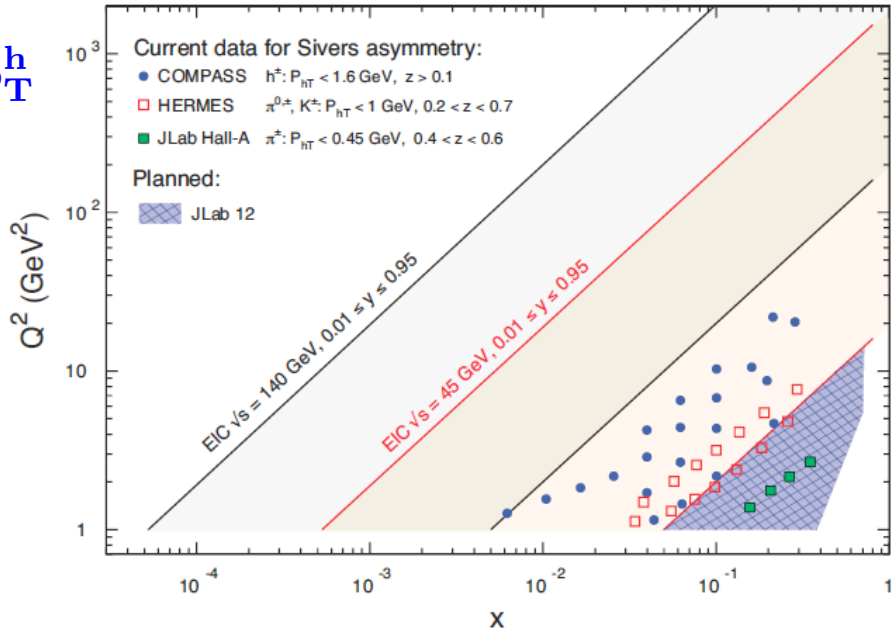

anisotropy due to transverse proton polarization in y direction

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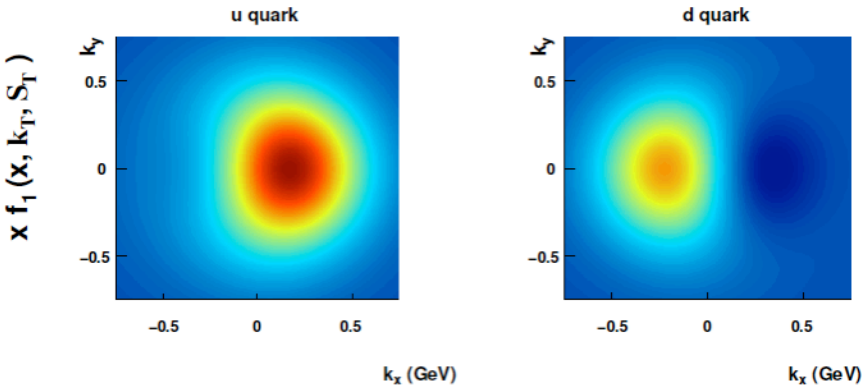

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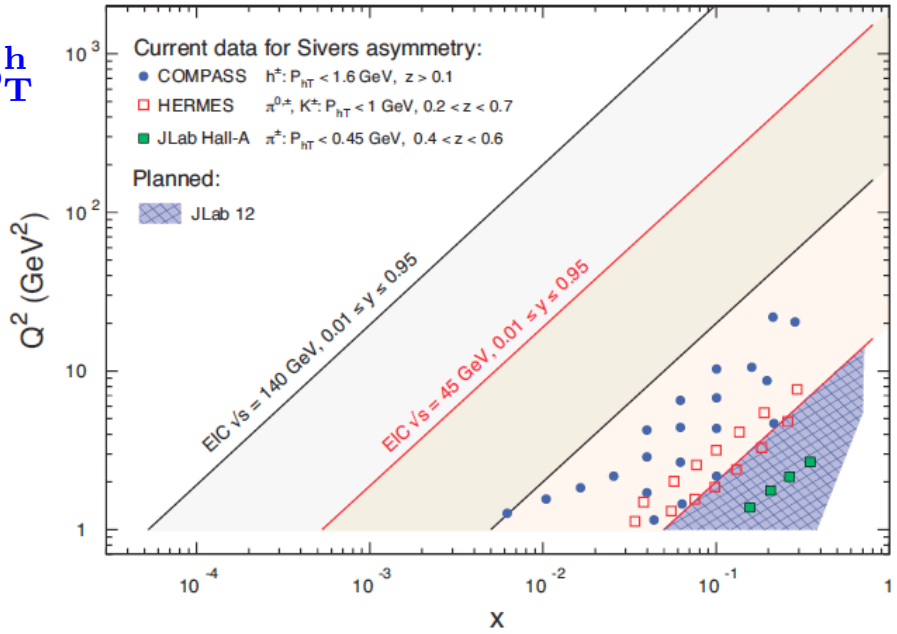

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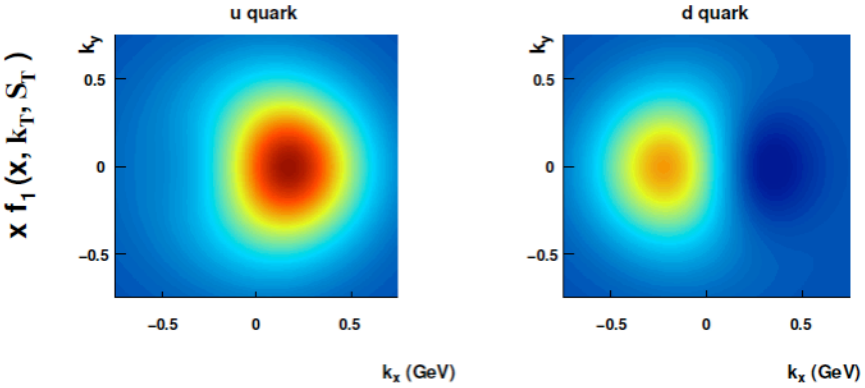

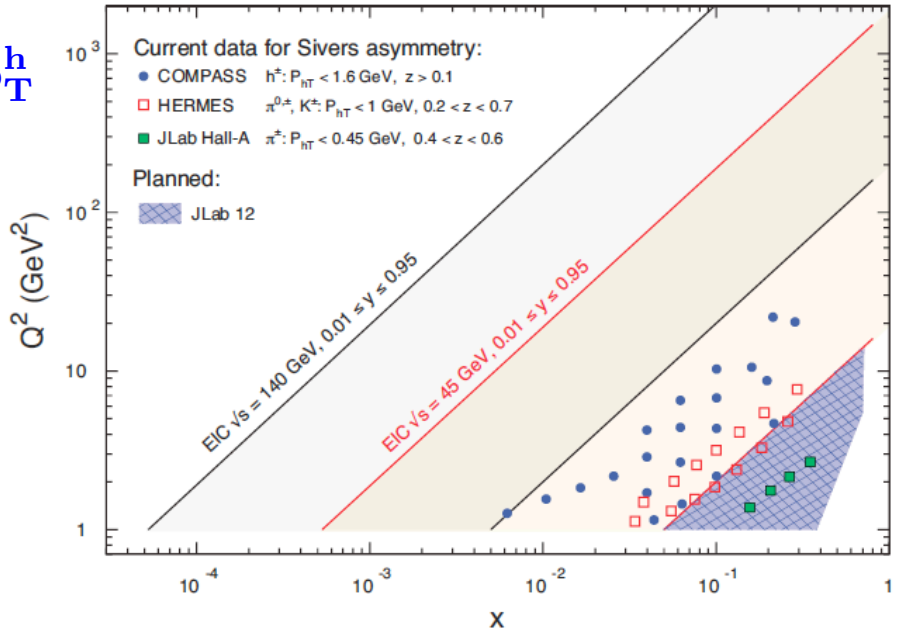

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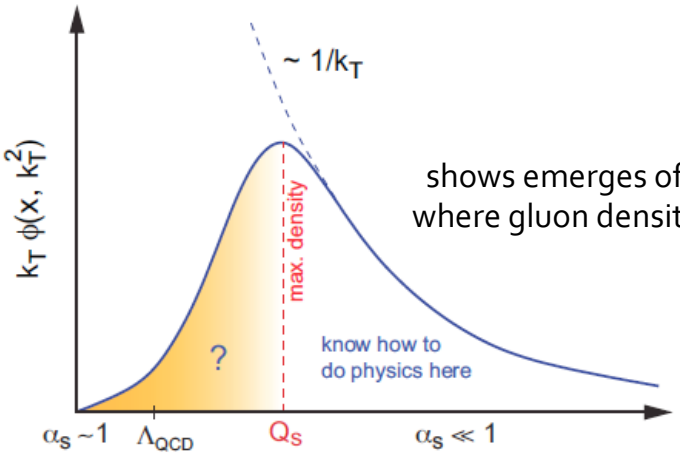
- origin of certain TMDs deeply linked with color gauge invariance of QCD
- unintegrated gluon density has **connection to CGC physics at small x**



shows emerges of a scale Q_s where gluon density saturates

specific example: Sivers function

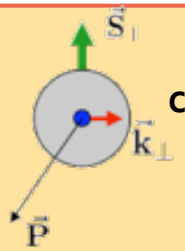
- slew of different TMDs can be measured by selecting certain ϕ modulations

example: **Sivers function**

measure

$\sin(\phi_h - \phi_S)$

modulation



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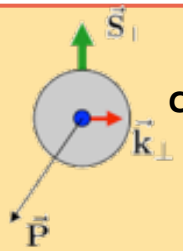

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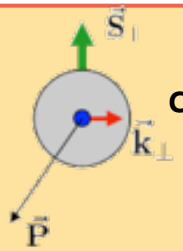

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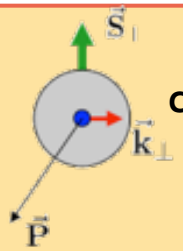

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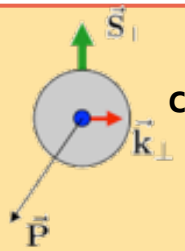

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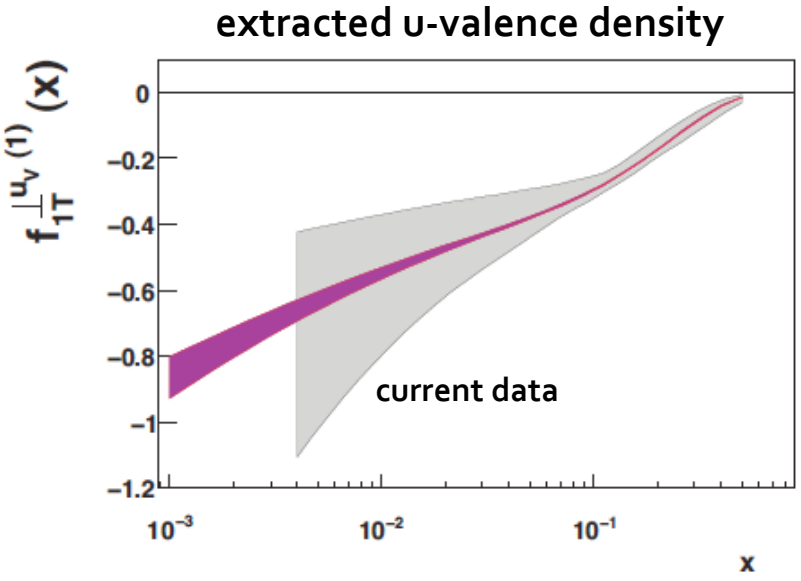
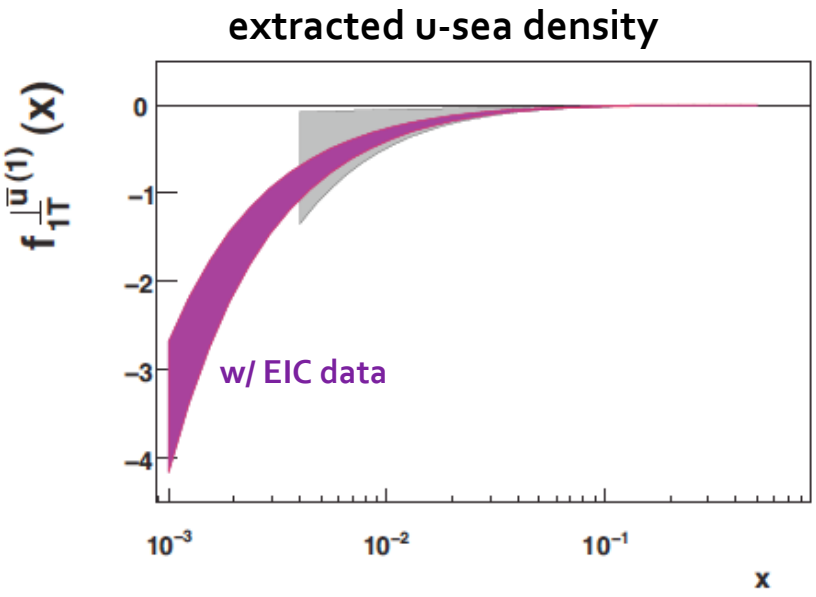
Sivers asymmetry has been observed only in the valence quark regime

prospects for Sivers related measurements





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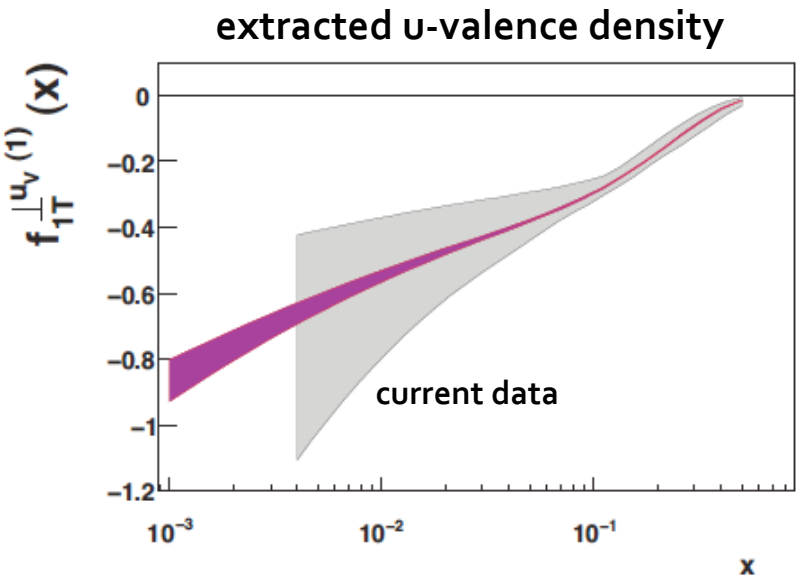
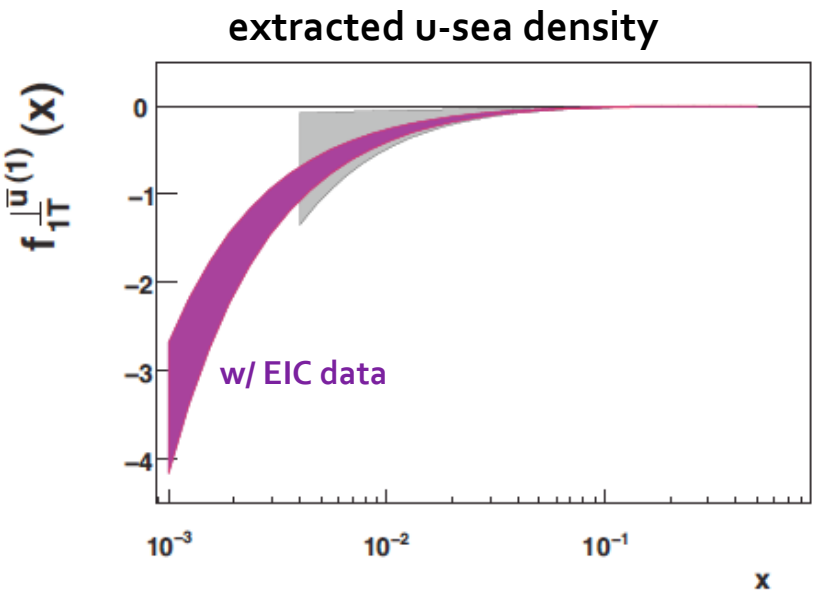
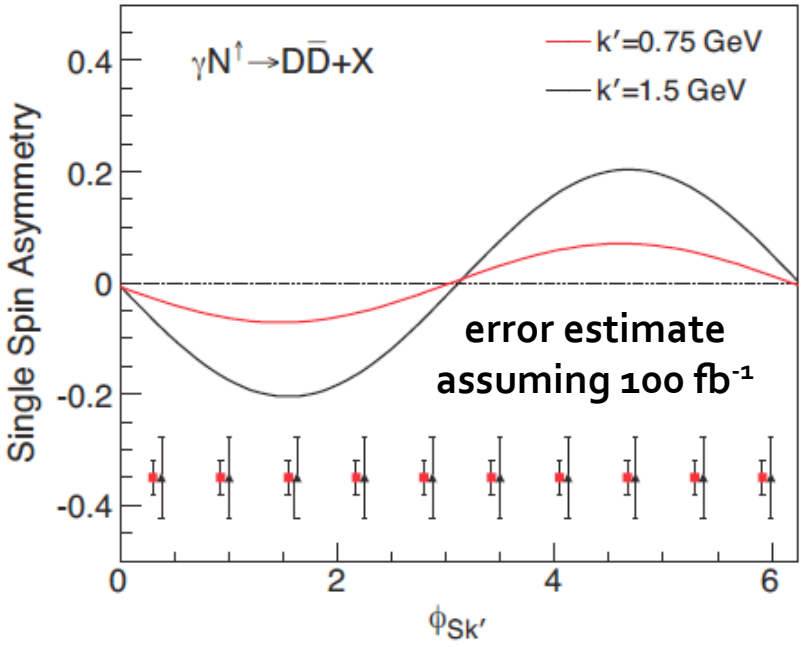




so far unmeasured **gluon Sivers fct** can be probed in D-meson correlations

observable: azimuthal asymmetry correlating the total k_T of the D-meson pair with transverse spin of the nucleon



angle between proton spin and k_T of D-meson pair

probing saturation with di-hadron correlations

- corresponding measurement in dAu at RHIC one of the best hints for saturation right now
- much cleaner probe in eA: no spectator background from electron side

tests universality of high gluon density framework between eA and pA

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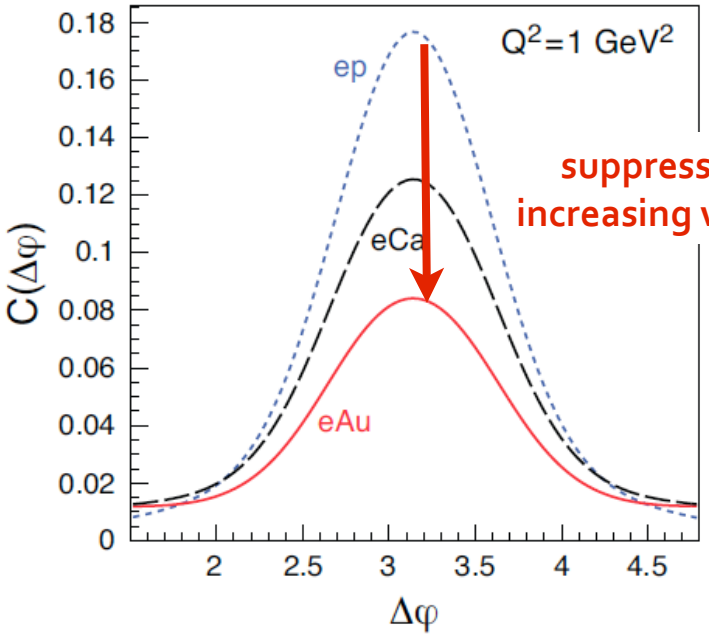

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$$\mathbf{p_T^{trig} > 2\,GeV}$$

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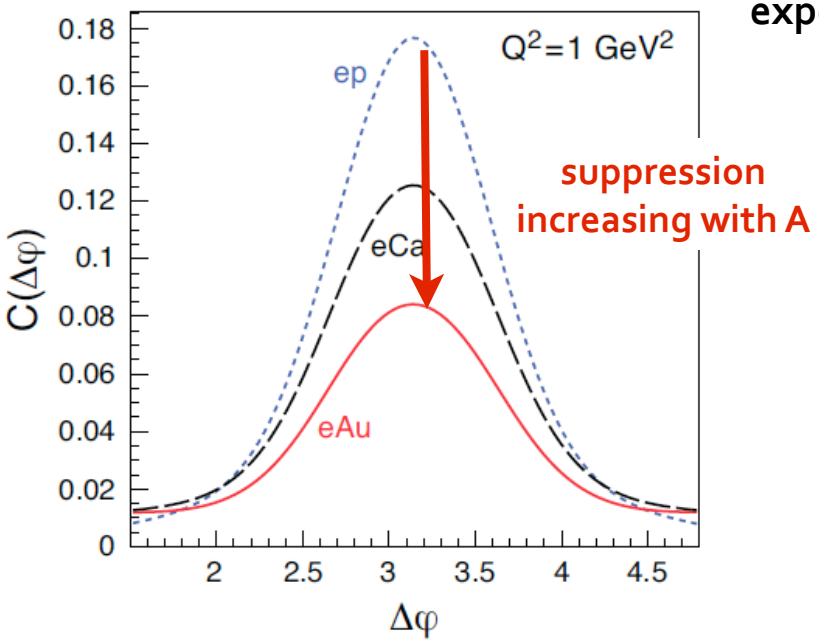

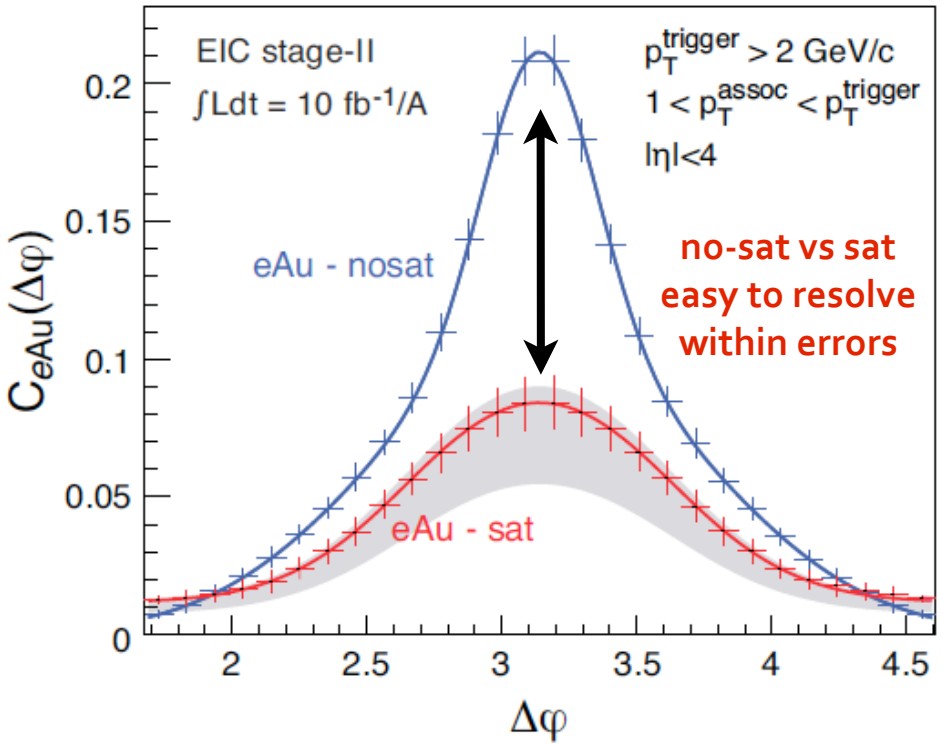

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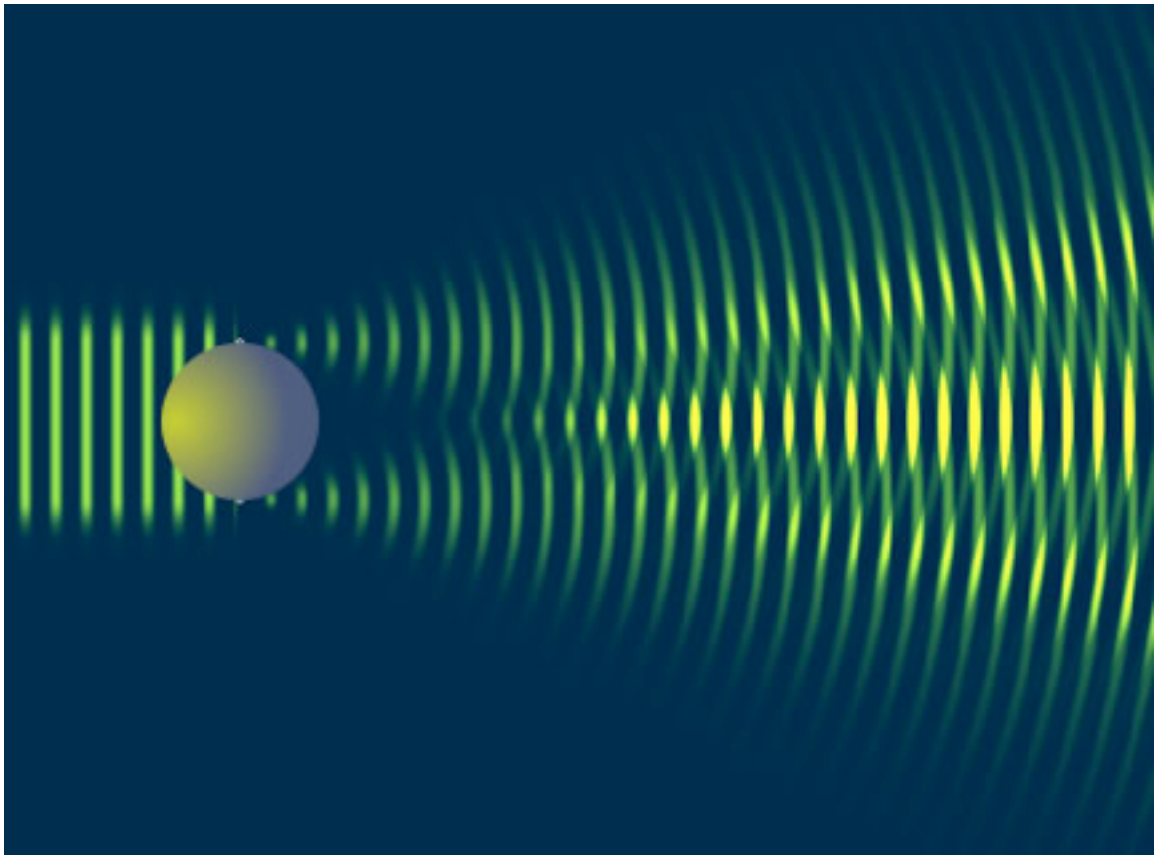

diffractive / exclusive processes

what to measure

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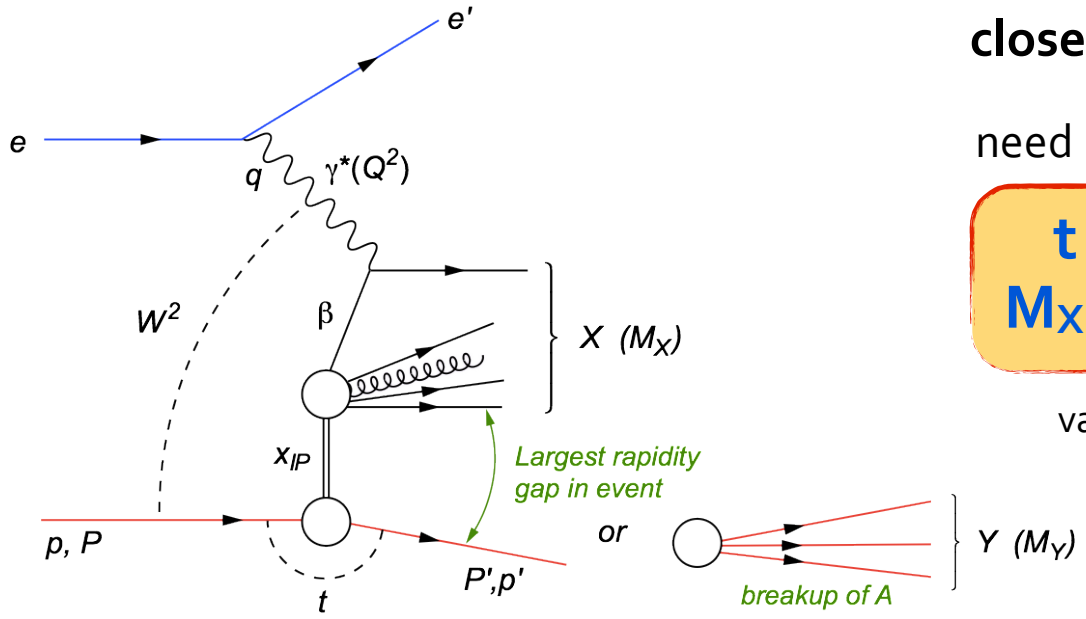

close relative of DIS

need in addition

t : momentum transfer squared

M_X : mass of diffractive final-state

variables can be traded for β and x_P
where $x_{Bj} = \beta\, x_P$

diffractive event characterized by large **rapidity gap** (angular region w/o particle flow)
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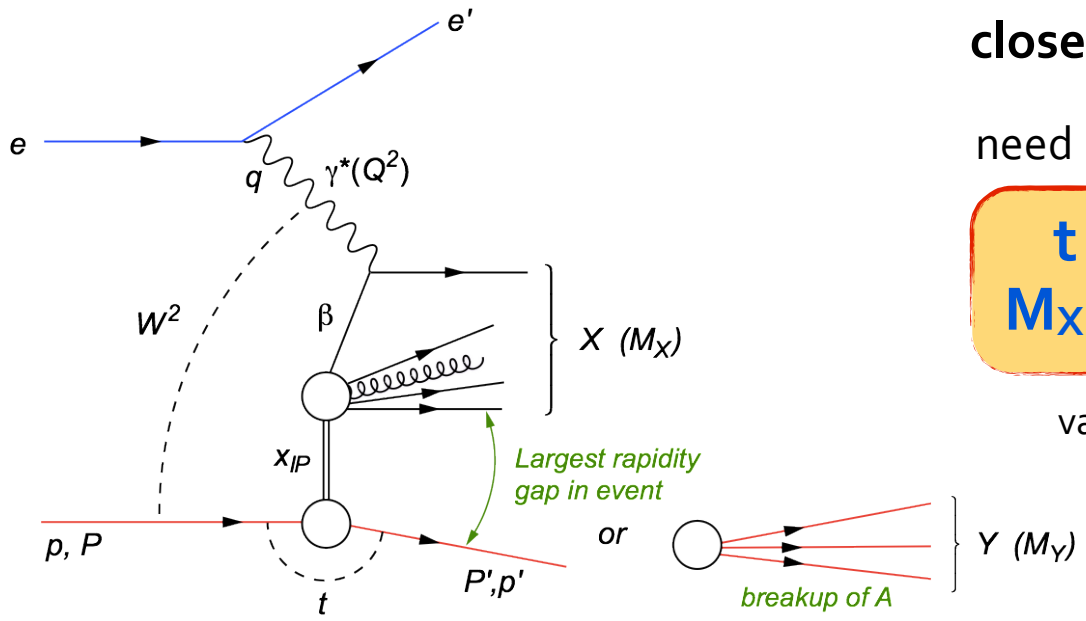

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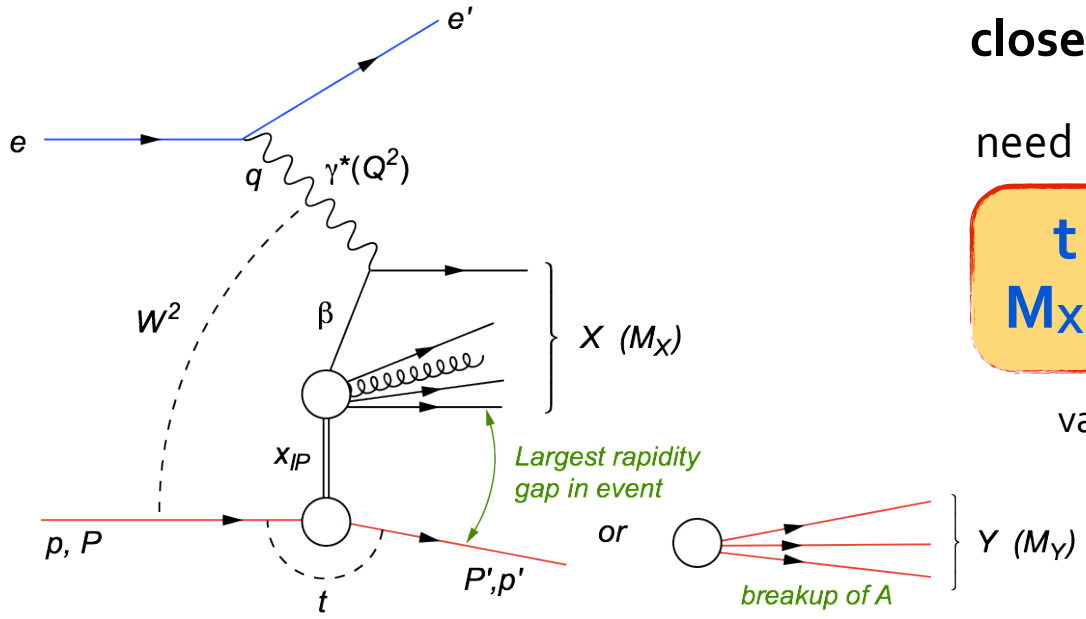

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- ep: detect intact protons in forward detectors

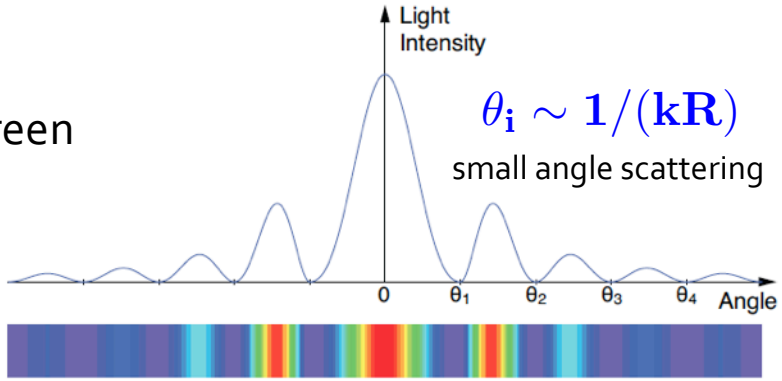
critical: IR design

- eA: need to tag on emitted neutrons from nuclear breakup (shown to be possible with near 100% efficiency)

diffractive physics - why relevant?

recall: diffractive pattern in optics

position of minima θ_i related to size R of screen



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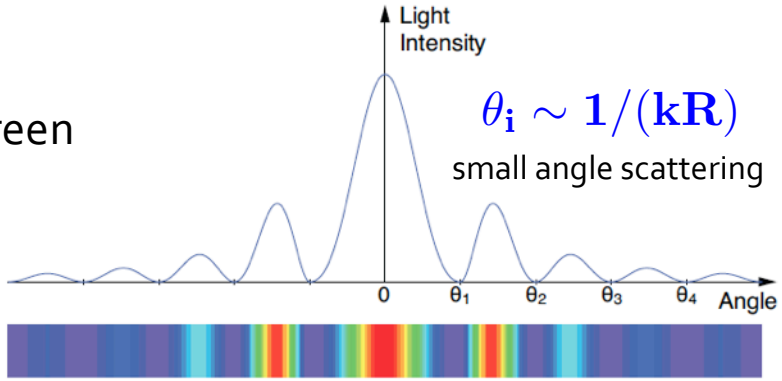

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dσ/dt resembles diffractive pattern

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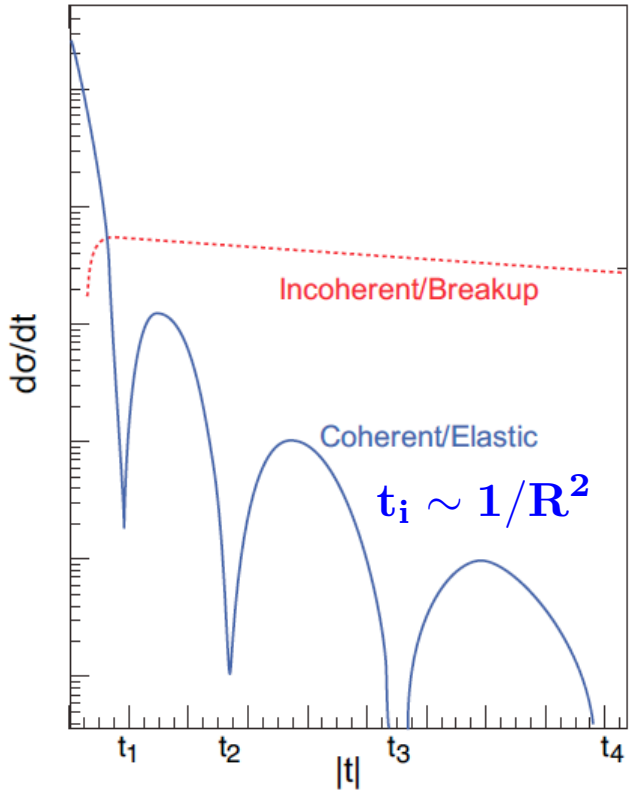

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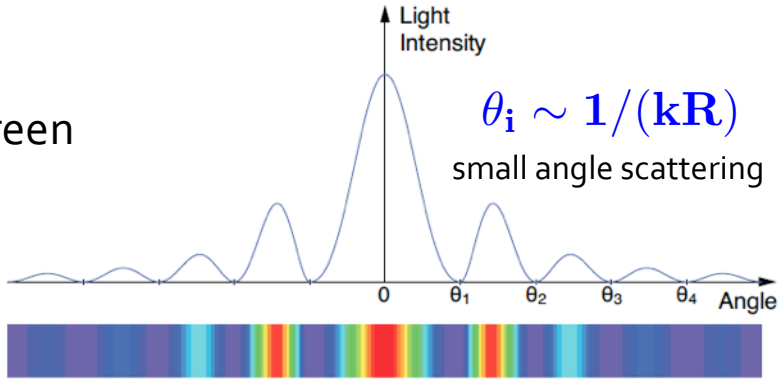

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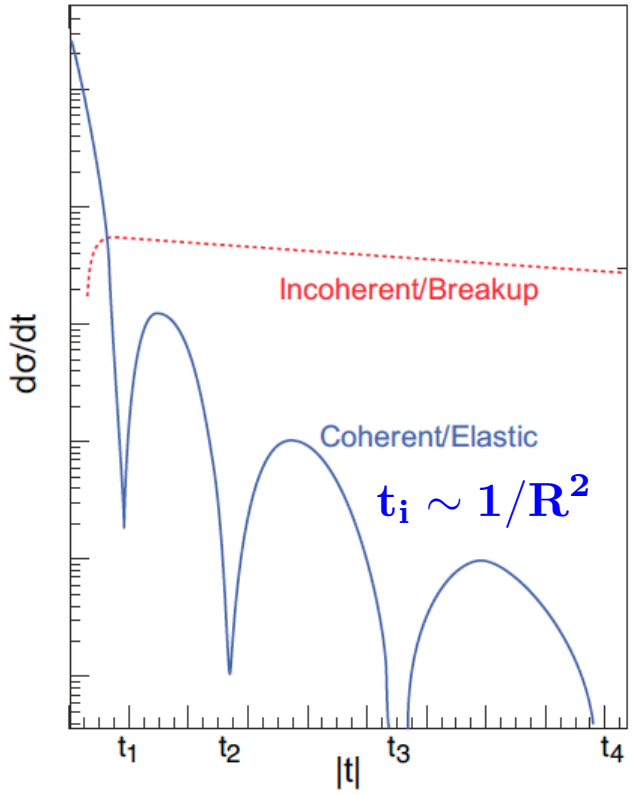

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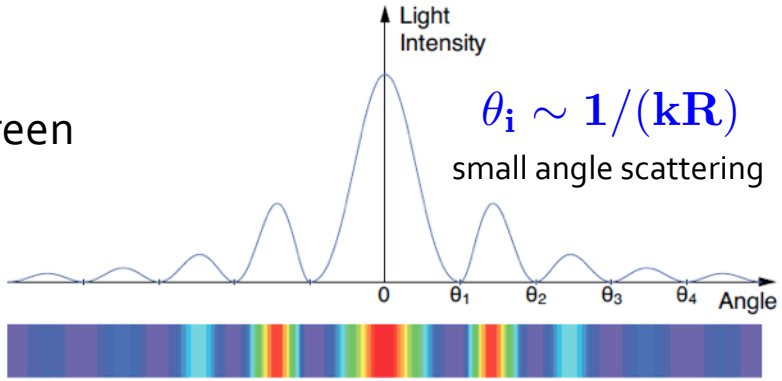

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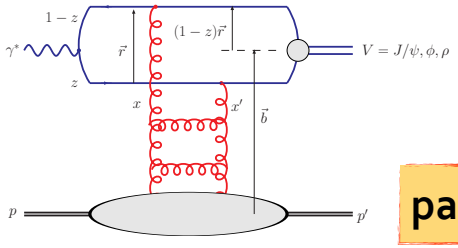
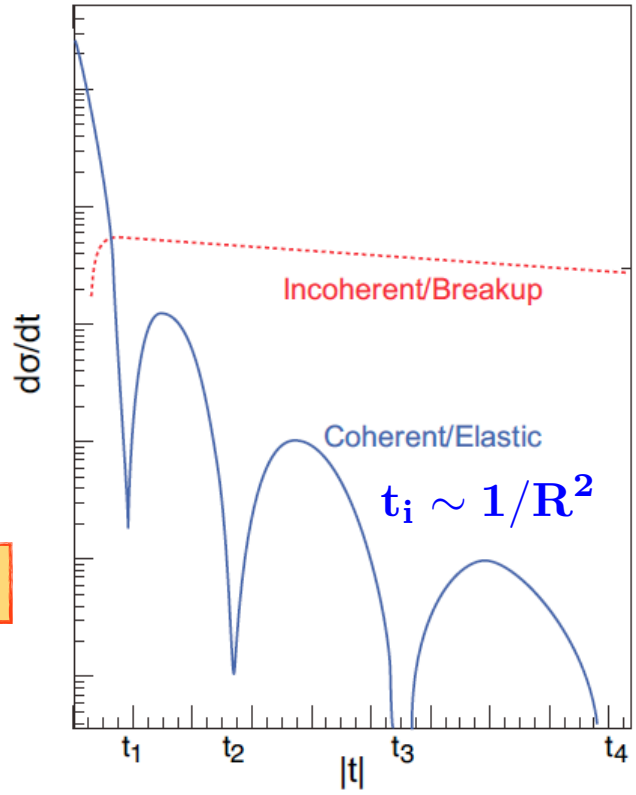
strong sensitivity to gluons



$d\sigma \sim [g(x)]^2$

due to required
color-neutral exchange

particularly sensitive to saturation



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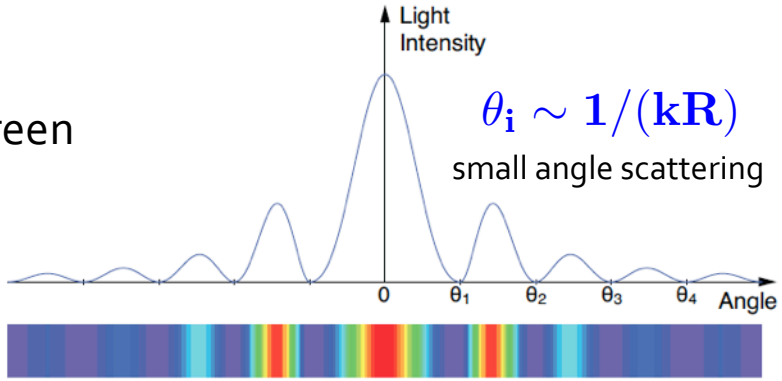

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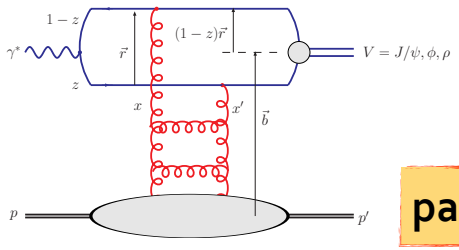
dσ/dt resembles diffractive pattern

where $|t| \approx k^2\theta^2$

crucial differences:

- target not always "black disc"
  → sensitivity to "size" of probe / onset of black disc limit
- incoherent (inelastic) contribution

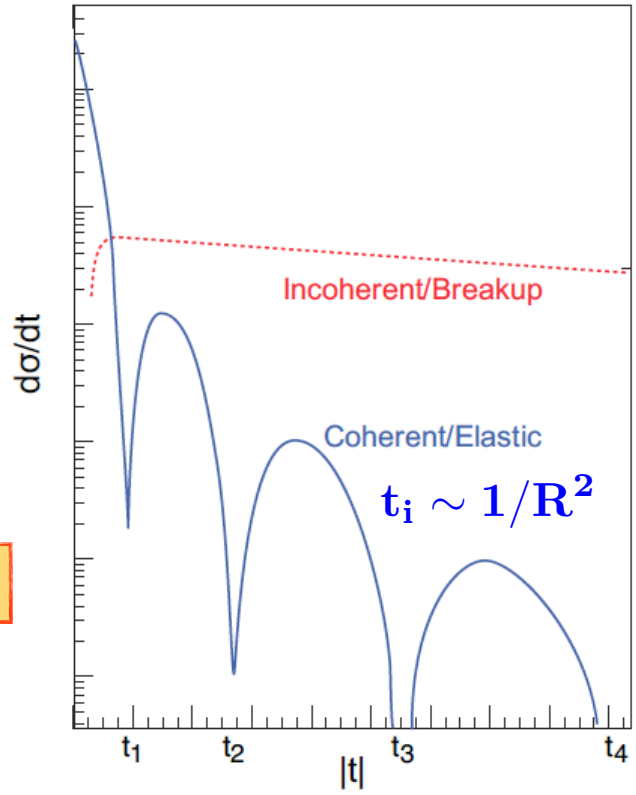
strong sensitivity to gluons



$d\sigma \sim [g(x)]^2$

due to required
color-neutral exchange

particularly sensitive to saturation



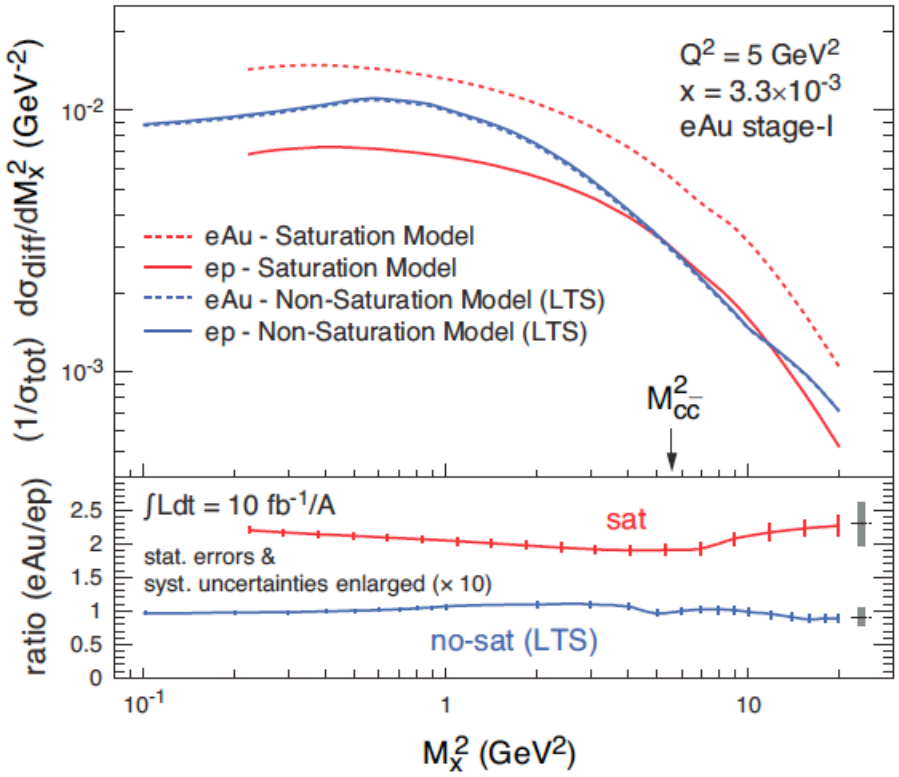
bonus: $\frac{d\sigma}{dt}$ ⟷ (Fourier transform) **spatial distribution of gluons**

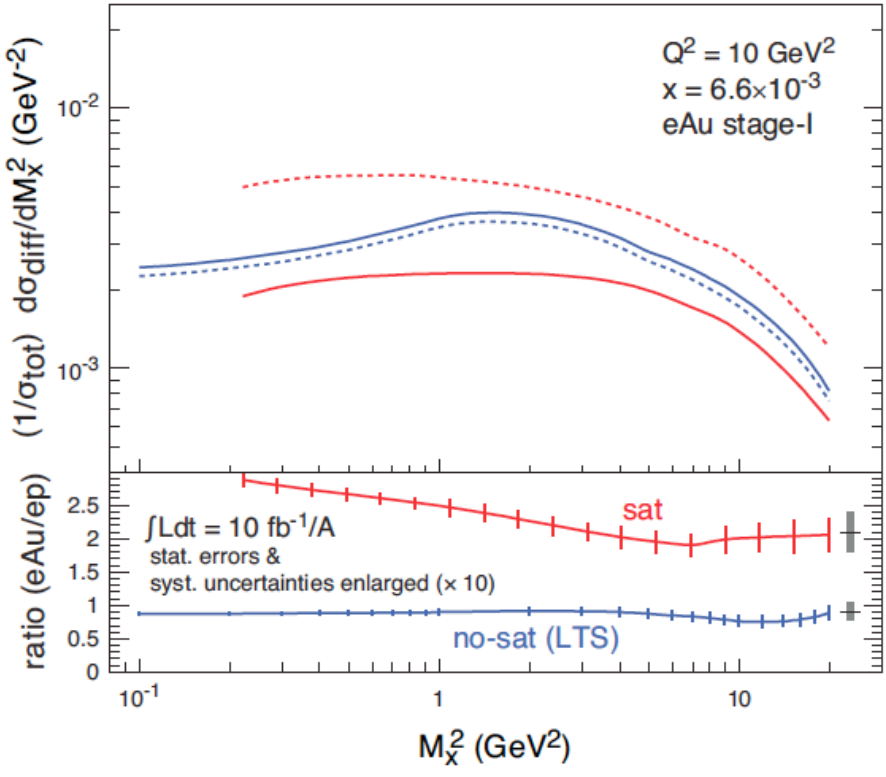
ratio of diffractive to total cross section

- black disc limit characterized by $\sigma_{\mathrm{diff}}/\sigma_{\mathrm{tot}} = 1/2$ (recall: HERA sees ≈1/7 in ep)

  →large fraction of diffractive event is unambiguous signature for reaching the saturated limit

estimates for fraction of low-mass coherent diffraction in ep and eA at EIC kinematics:





find:

- w/o non-linear effects eA/ep ratio stays roughly one
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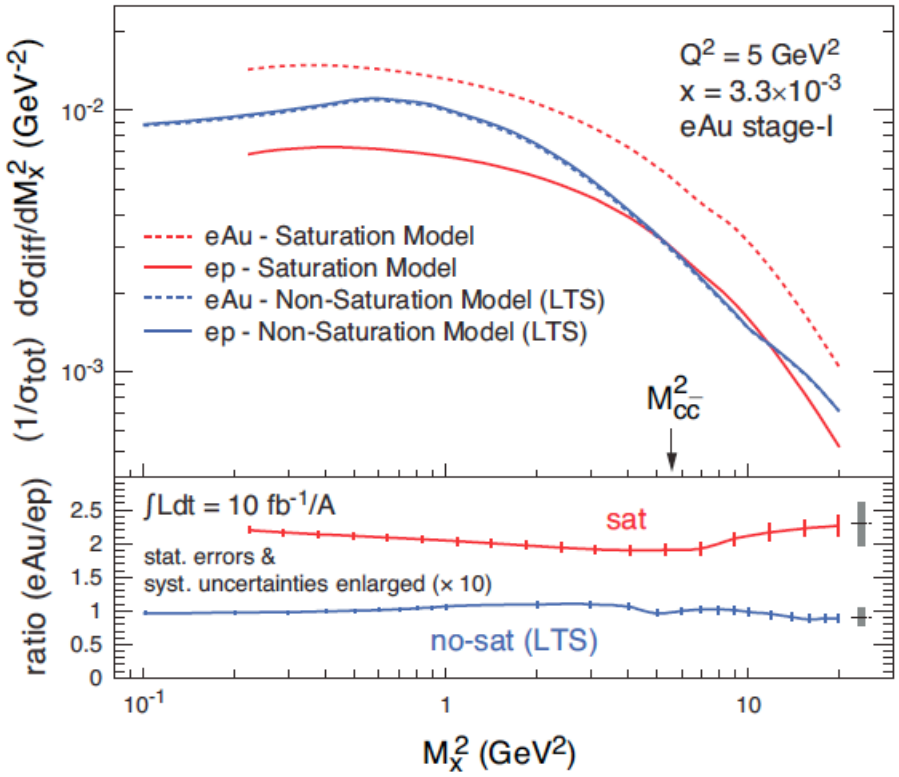

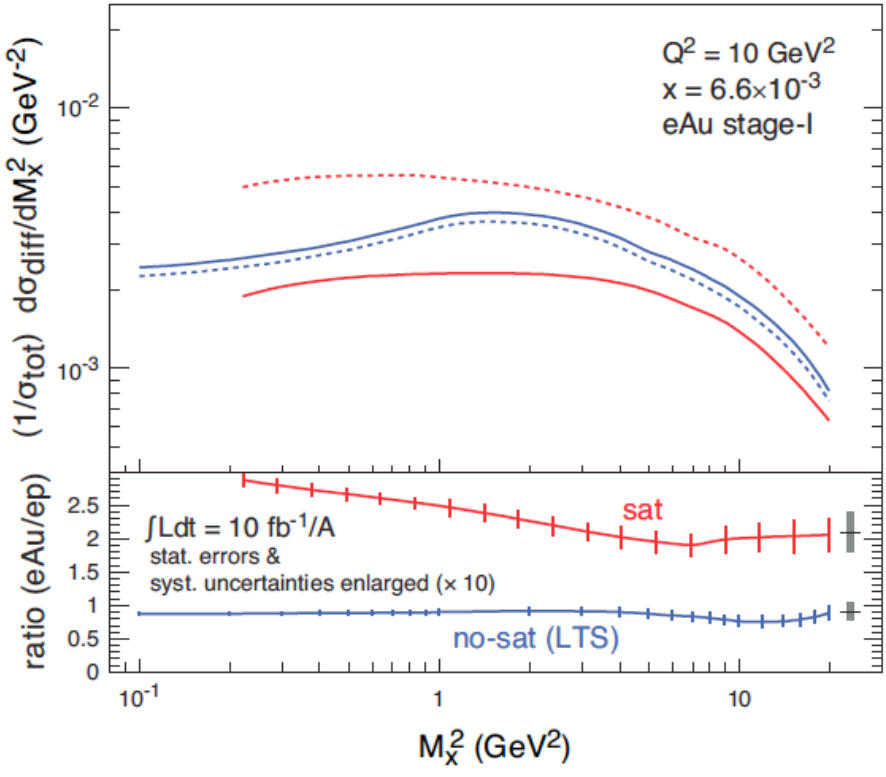

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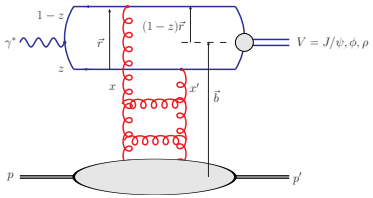
day-1 signature for saturation at an EIC

exclusive vector meson production

- **unique probe** - allows to measure momentum transfer t in eA diffraction

$$\mathbf{t} = (\mathbf{p_A} - \mathbf{p_{A'}})^2 = (\mathbf{p_{VM}} + \mathbf{p_{e'}} - \mathbf{p_e})^2$$

in general, one cannot detect the outgoing nucleus and its momentum



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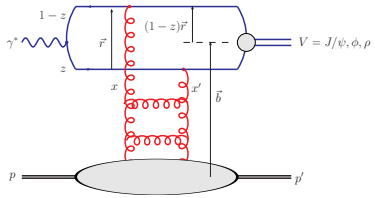

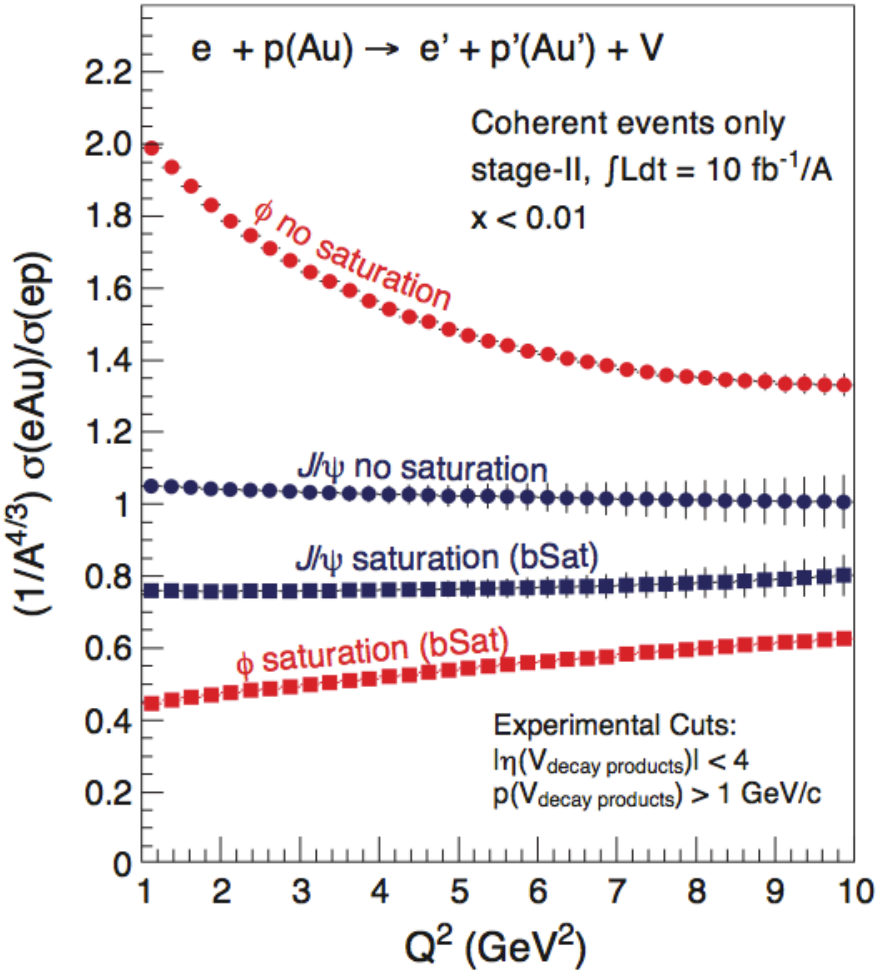

cross section strongly depends on overlap with VM wave function

- **small size (J/Ψ)**
  cuts off saturation region in dipole amplitude
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  "sees more of dipole amplitude"
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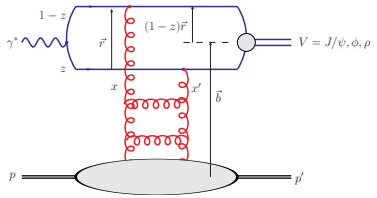

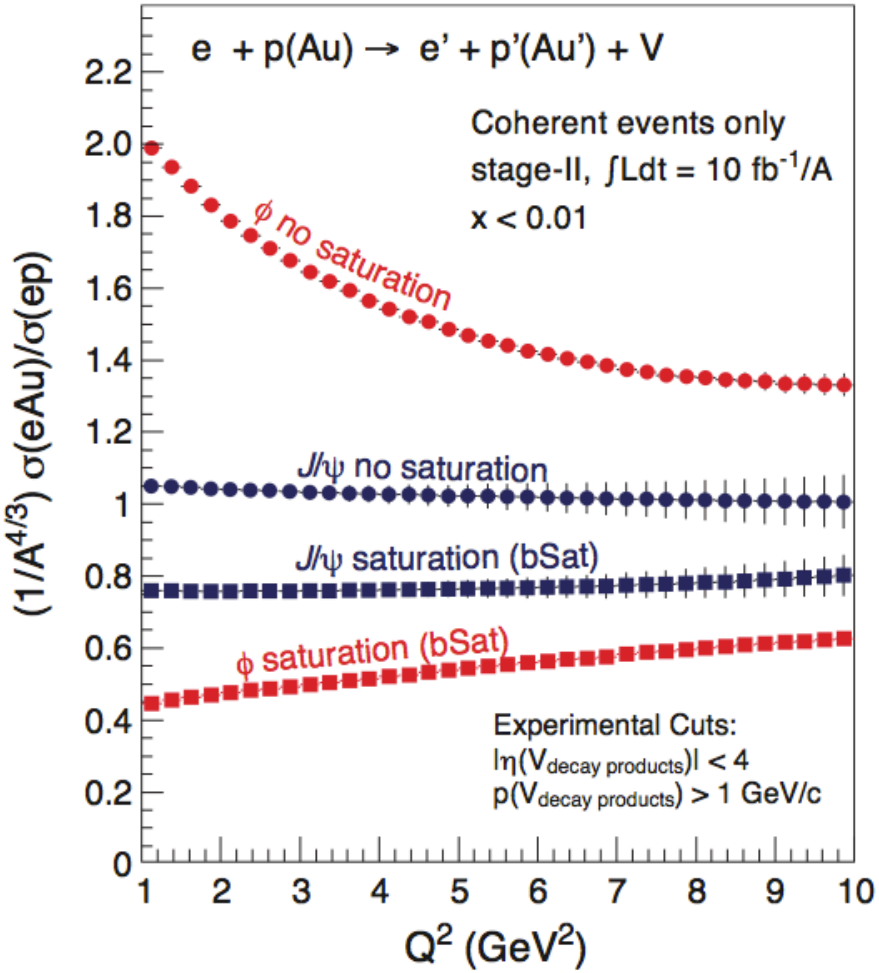

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Q^2 variation controls size of probe
→ go in (small Q^2) and out (large Q^2) of saturation region

spatial distribution of gluons through diffraction

goal: going after the source distribution of gluons through **Fourier transform of dσ/dt**

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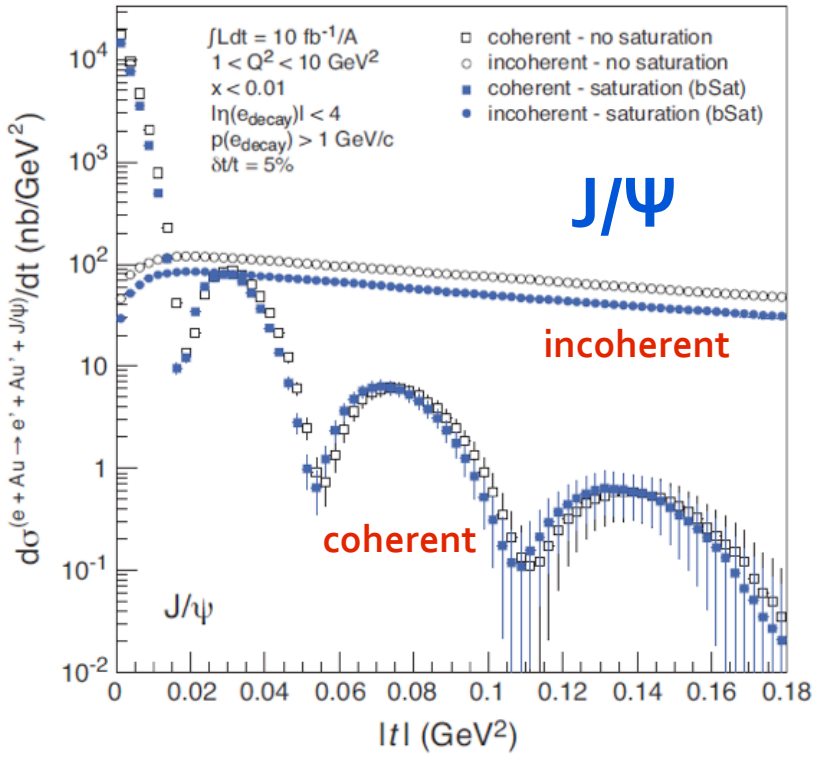
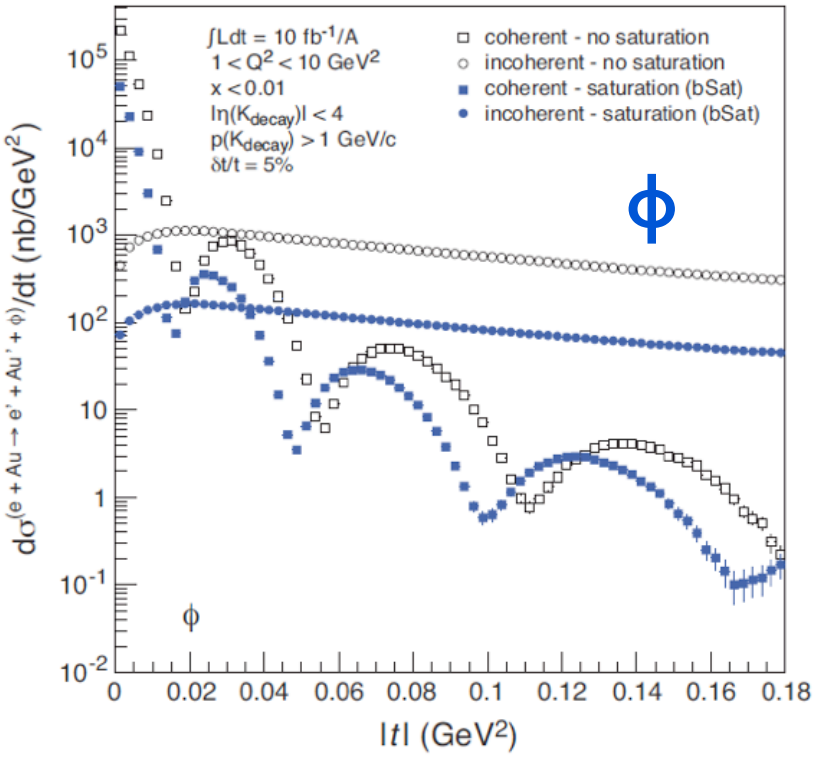
find:

- typical diffractive pattern for coherent (non-breakup) part
- as expected, J/Ψ less sensitive to saturation effects than larger ϕ meson





how does the imaging work - what do we learn?

idea: momentum transfer t conjugate to transverse position (impact parameter b)

→ expect small t relevant for large b and vice versa

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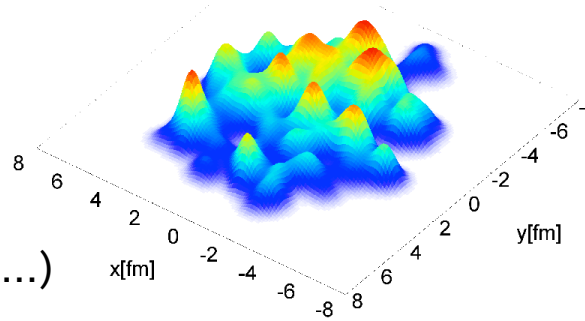

→ impact on our understanding of initial conditions of heavy ion collisions

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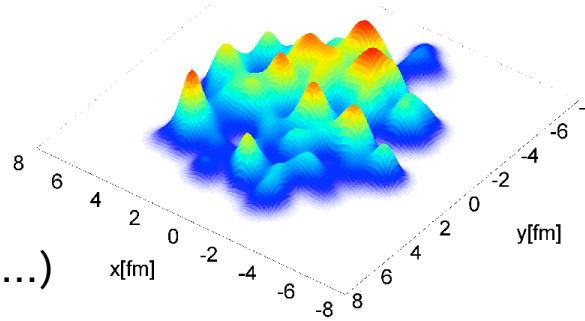

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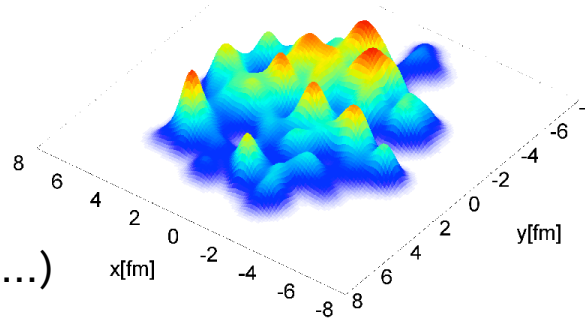

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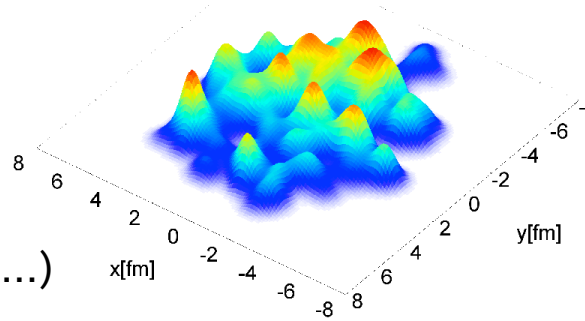

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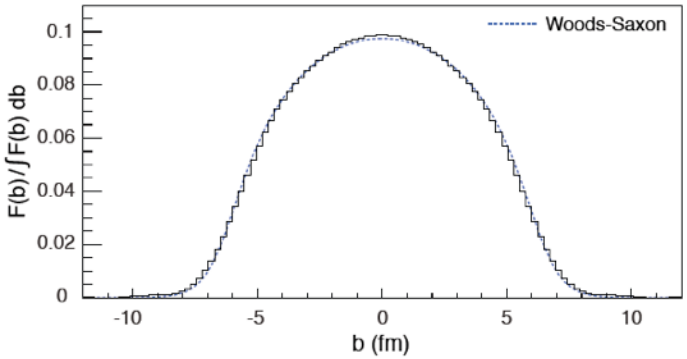
... so, does it work at all?

✓ yes, $|t|<0.15$ GeV^2 enough in eA to reconstruct Woods-Saxon potential used in simulation

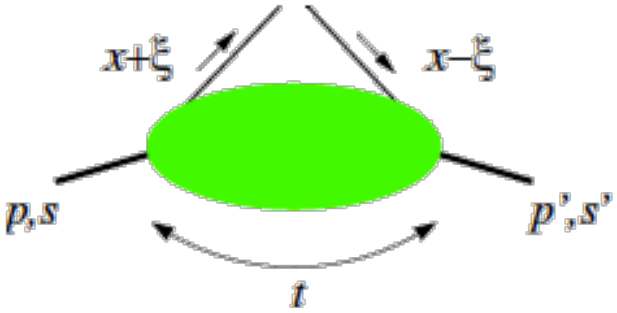


exclusive processes and GPDs

another class of (related) processes for **parton imaging**

need to introduce concept of

generalized parton distributions (GPDs)



GPDs depend on:

- momentum transfer t
- resolution scale Q
- long. momentum before and after the scattering: x, ξ

= interference between different nucleon states (not a probability)

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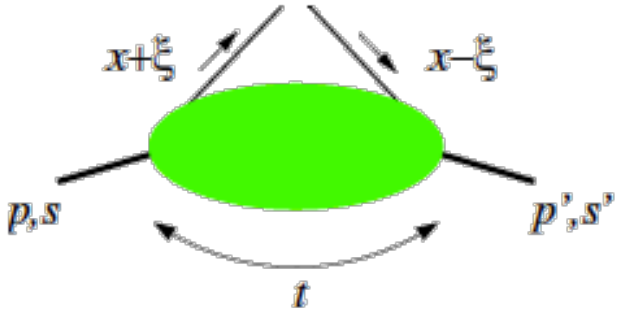

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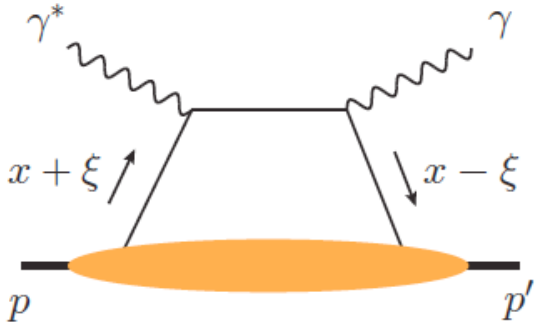
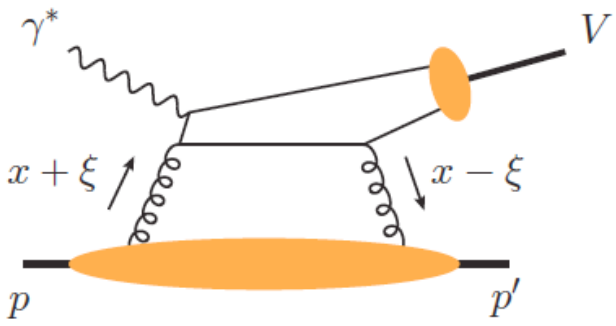
appear in theoretical description of **exclusive processes**



deeply virtual Compton scattering (DVCS)

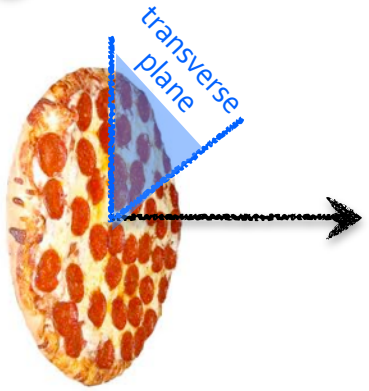


vector meson production

path to spatial imaging of partons through GPDs

recall: standard PDFs do not resolve transverse positions in the nucleon

fast moving nucleon turns into a `pizza' but transverse size remains ≃ 1 fm



compelling questions

- how are quarks and gluons spatially distributed
- how do they move in the transverse plane
- do they orbit and do we have access to spin-orbit correlations

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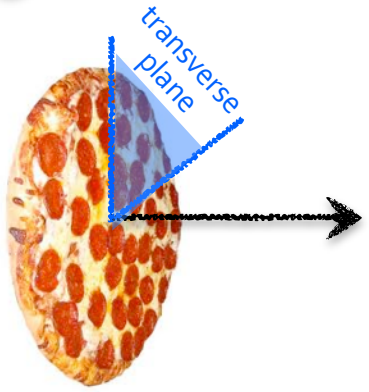

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already discussed

3-D

$f(x, k_T)$

transv. mom. dep. PDF

semi-inclusive DIS

$\int d^2k_T$

1-D

$f(x)$

parton densities

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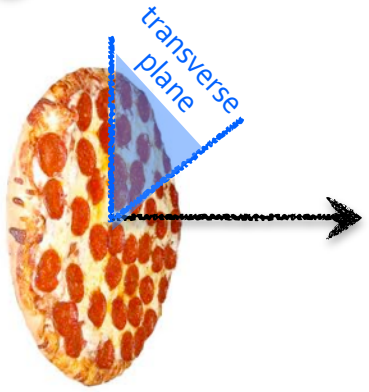

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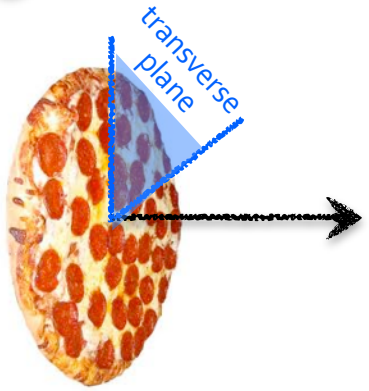

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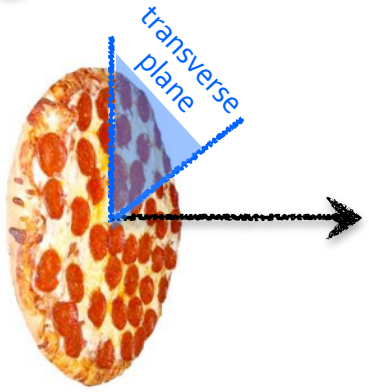

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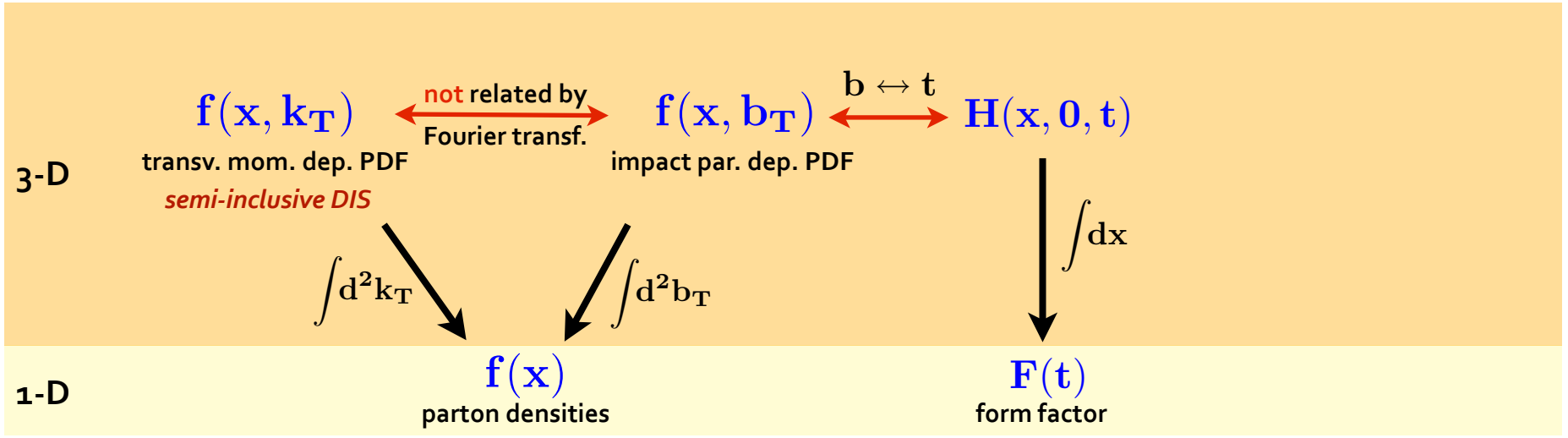

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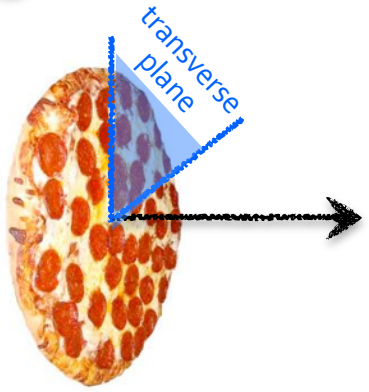

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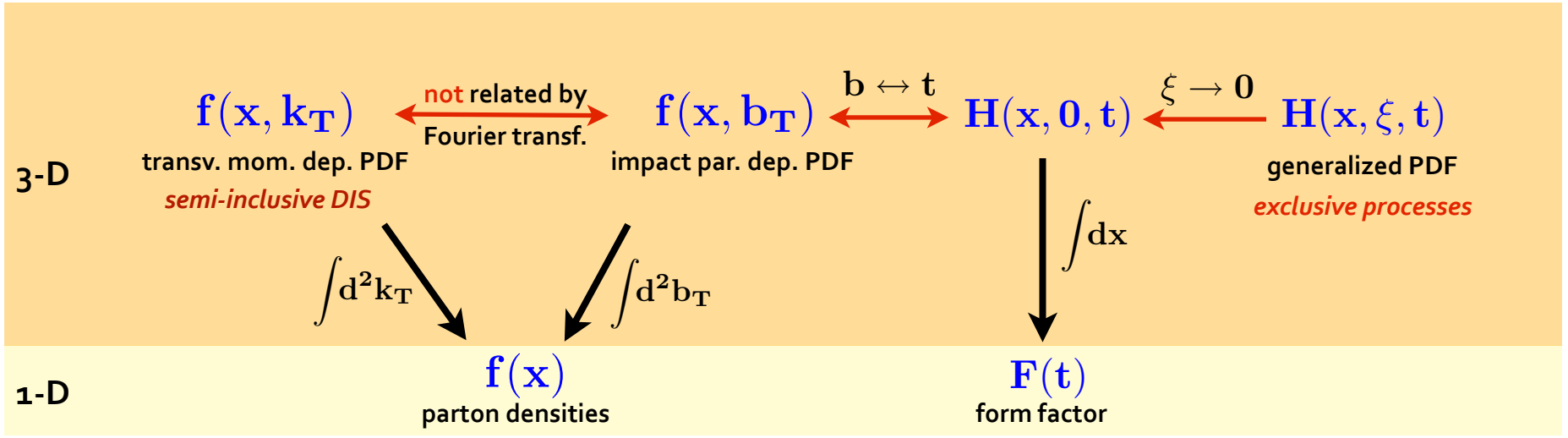

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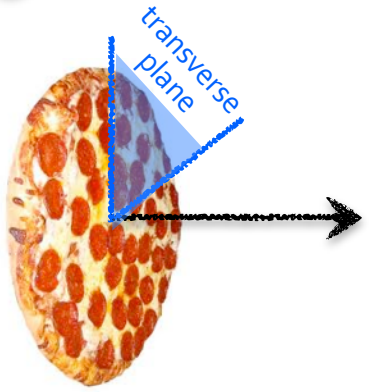

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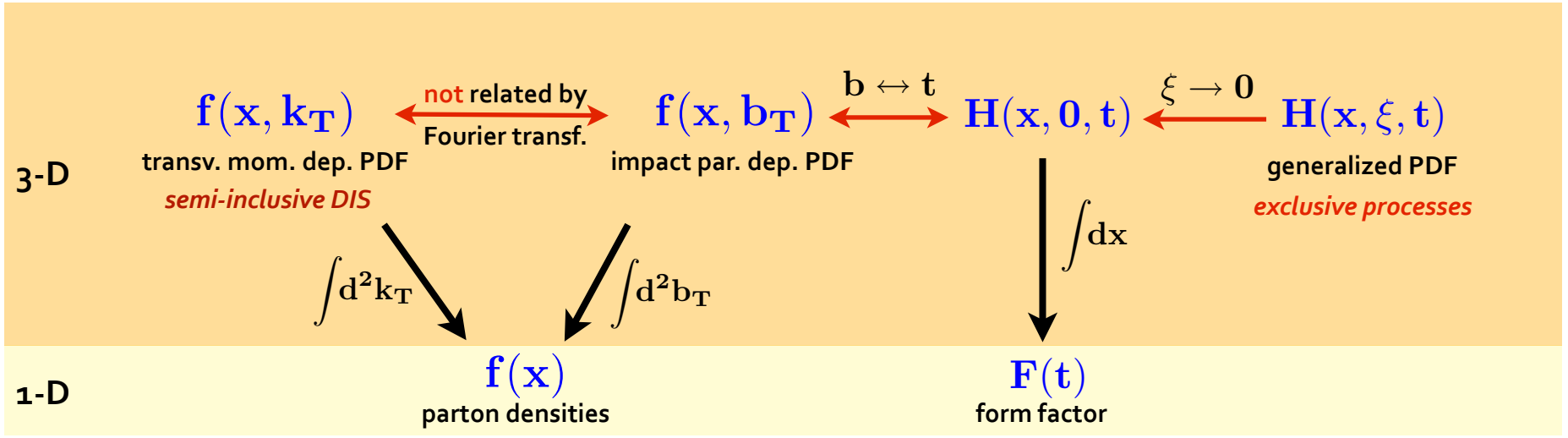

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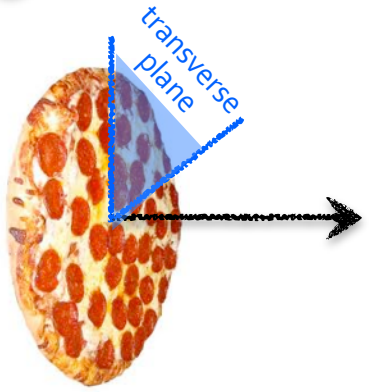

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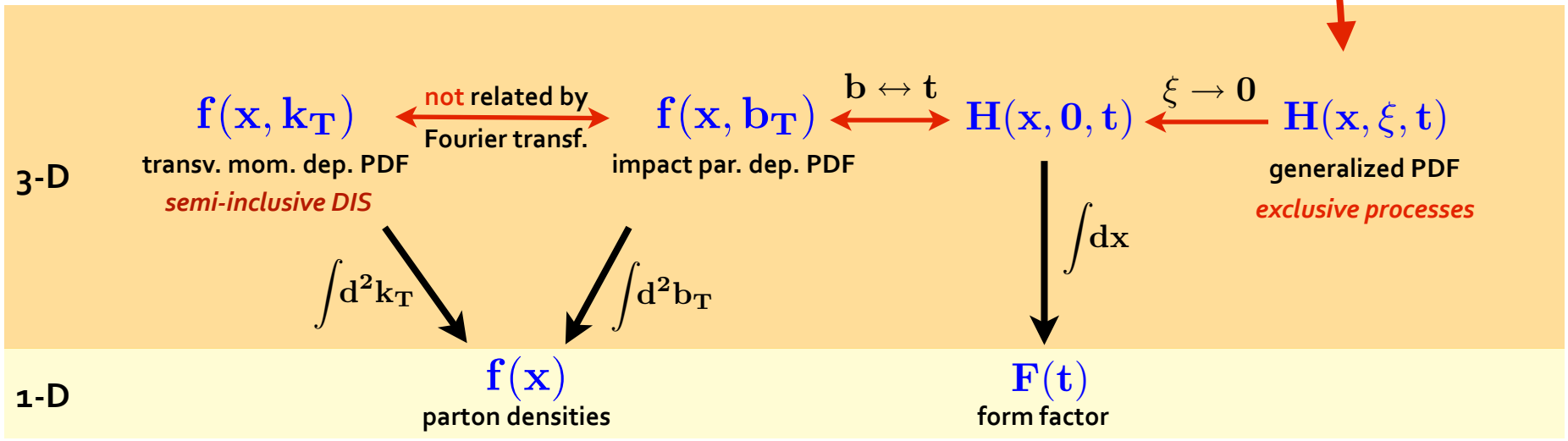

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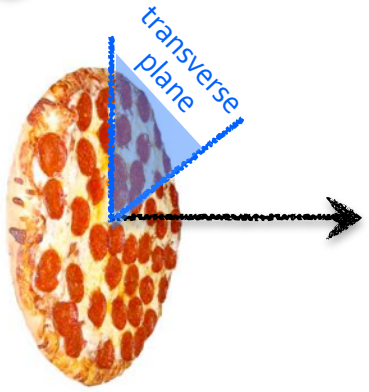

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GPD's appear here

again, need Fourier transform to get what we want

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not related by Fourier transf.

$f(x, b_T)$ — impact par. dep. PDF

$b \leftrightarrow t$

$H(x, 0, t)$

$\xi \to 0$

$H(x, \xi, t)$ — generalized PDF — *exclusive processes*

$\int d^2k_T$ $\int d^2b_T$ $\int dx$

1-D

$f(x)$ — parton densities

$F(t)$ — form factor

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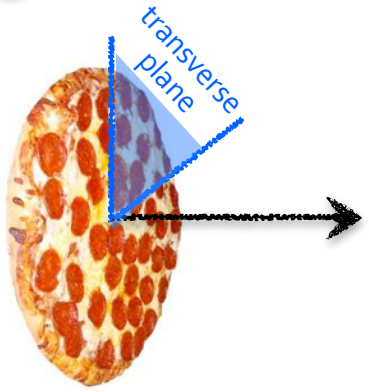

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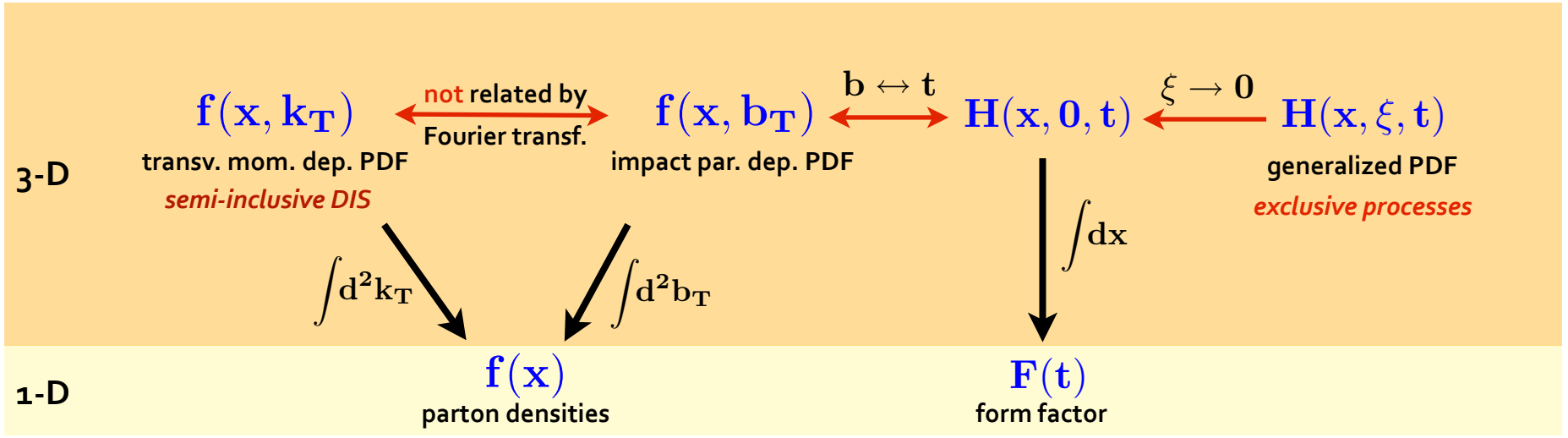

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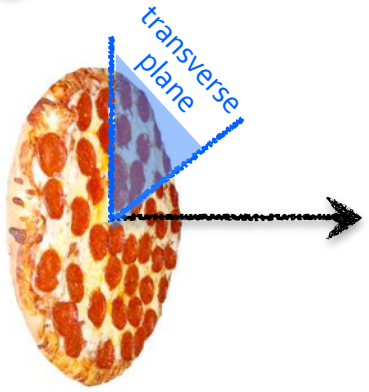
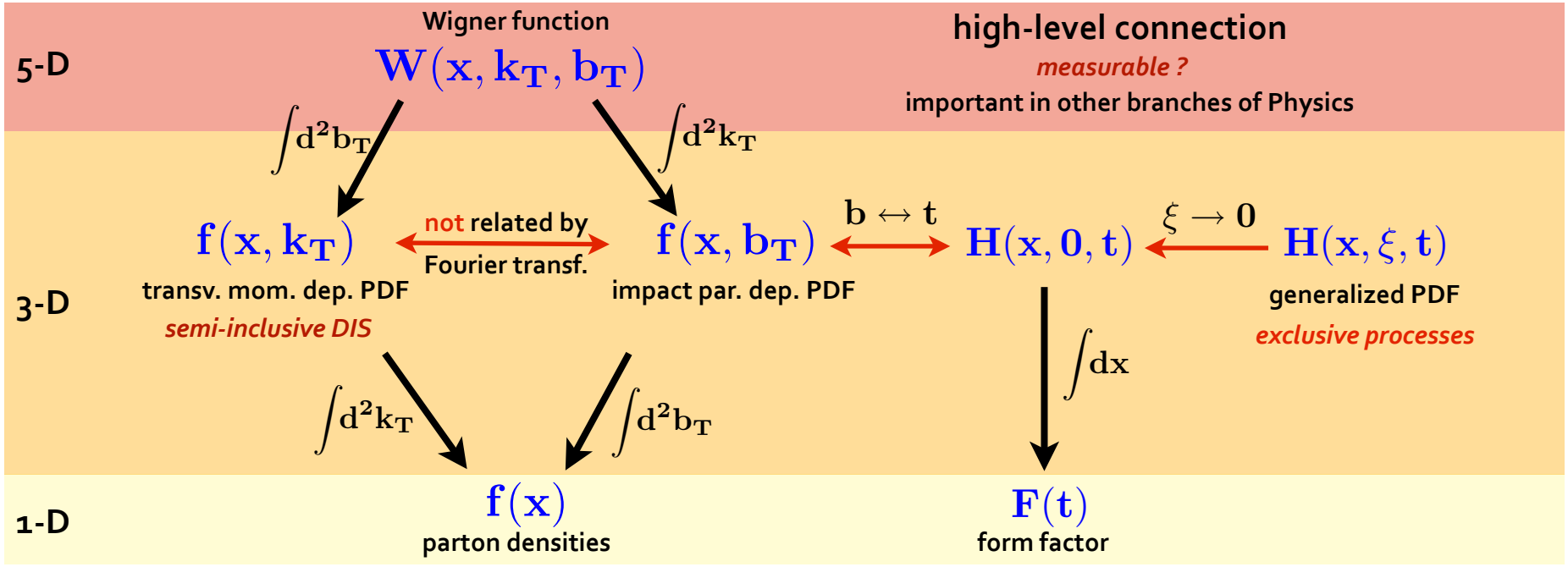
fast moving nucleon turns into a `pizza' but transverse size remains ≃ 1 fm



compelling questions

- how are quarks and gluons spatially distributed
- how do they move in the transverse plane
- do they orbit and do we have access to spin-orbit correlations



roadmap for transverse imaging of the proton

- obtain GPDs from global analysis of DVCS and vector meson data in ep scattering

  slew of angular & polarization observables (+ use of positron beams) to disentangle H and E

4 GPDs per flavor, e.g.,

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p', s'|\bar{q}(-\frac{z}{2})\,\mathcal{W}\,\gamma^+ q(\frac{z}{2})|p, s\rangle_{z^+=0,\mathbf{z}=\mathbf{0}}$$

$$= \quad H^q\,\bar{u}(p', s')\gamma^+ u(p, s) + E^q\,\bar{u}(p', s')\frac{i}{2m_p}\sigma^{+\alpha}(p' - p)_\alpha u(p, s)$$

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recover PDFs in limit

$$s = s', \xi = 0, t = 0$$

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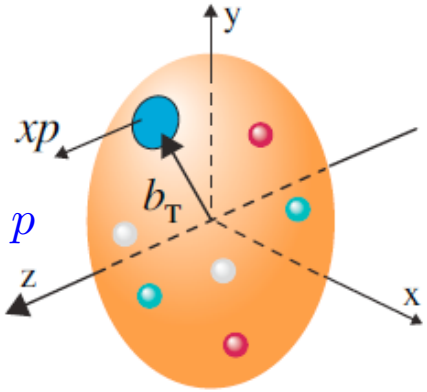
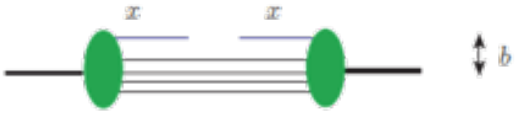
e.g. $q(x, b^2) \simeq \int d^2\boldsymbol{\Delta} e^{-ib\boldsymbol{\Delta}} H^q(x, \xi = 0, t = -\boldsymbol{\Delta}^2)$ where $\boldsymbol{\Delta} = p' - p$



gives distribution of quarks with



- longitudinal momentum fraction x
- transverse distance b from proton center

roadmap for transverse imaging of the proton

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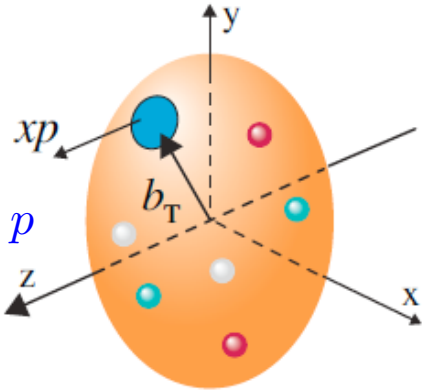

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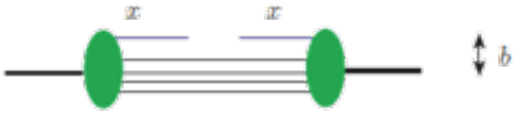


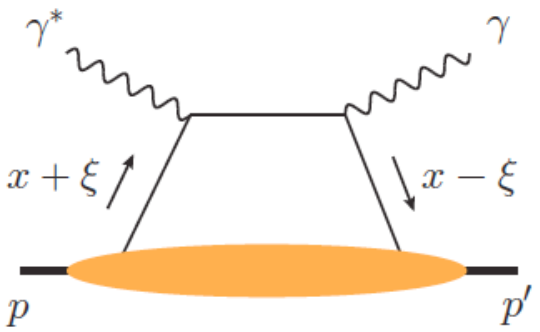
- longitudinal momentum fraction x
- transverse distance b from proton center

challenges:

- need to resolve small distances in proton
- no diffractive pattern in accessible t range

→ need dσ/dt in larger t-range than in eA

example: DVCS - what do we know?



- best understood and worked out theoretically
- x is integrated out in scattering amplitude
- ξ is related to usual Bjorken x of DIS: $\xi = x_{Bj} / (2\text{-}x_{Bj})$
- large number of angular and polarization observables
- interferes with genuine QED "Bethe-Heitler" process

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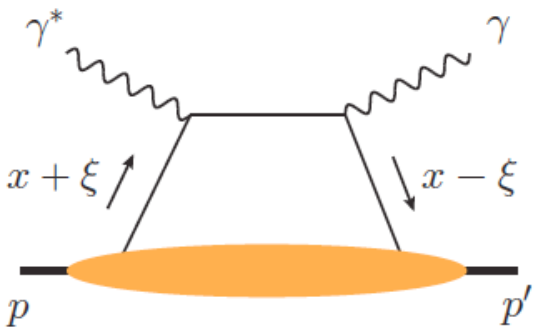

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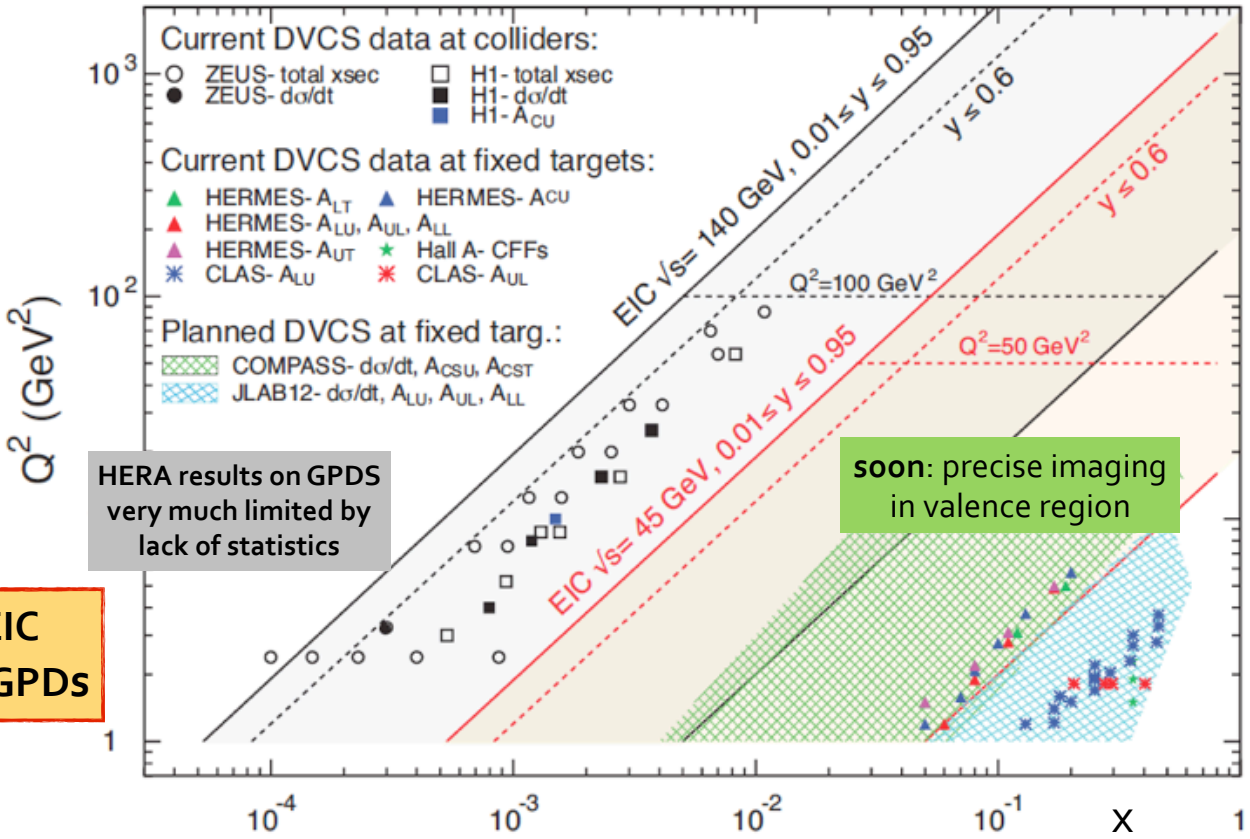
DVCS measurements past-present-future



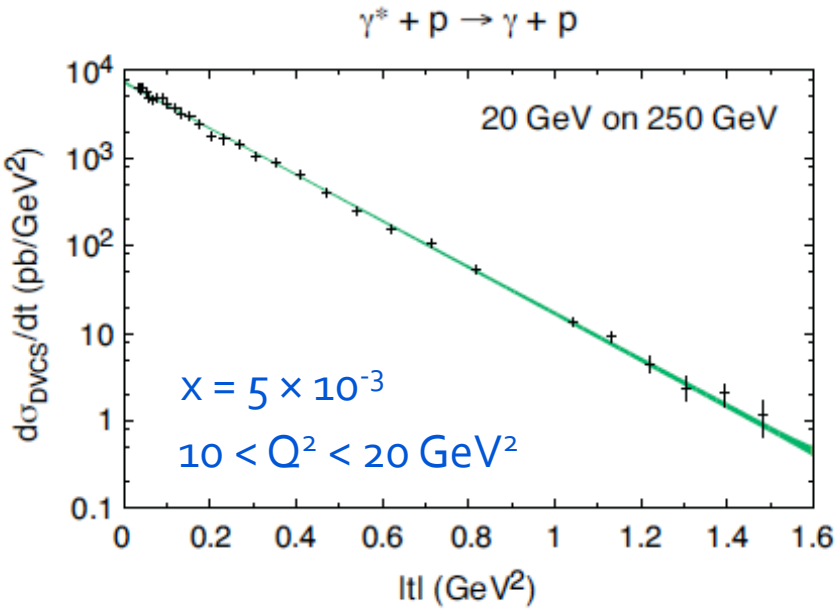
HERA results on GPDS very much limited by lack of statistics

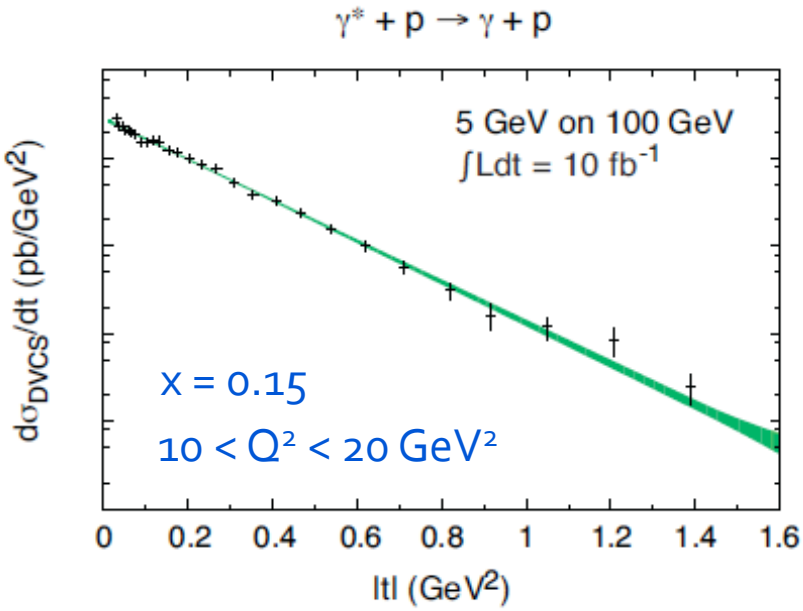
soon: precise imaging in valence region

plenty of opportunities at an EIC to map out gluon and sea-quark GPDs

DVCS - how well does it work out?

examples of simulated DVCS data including acceptance cuts and resolution effects





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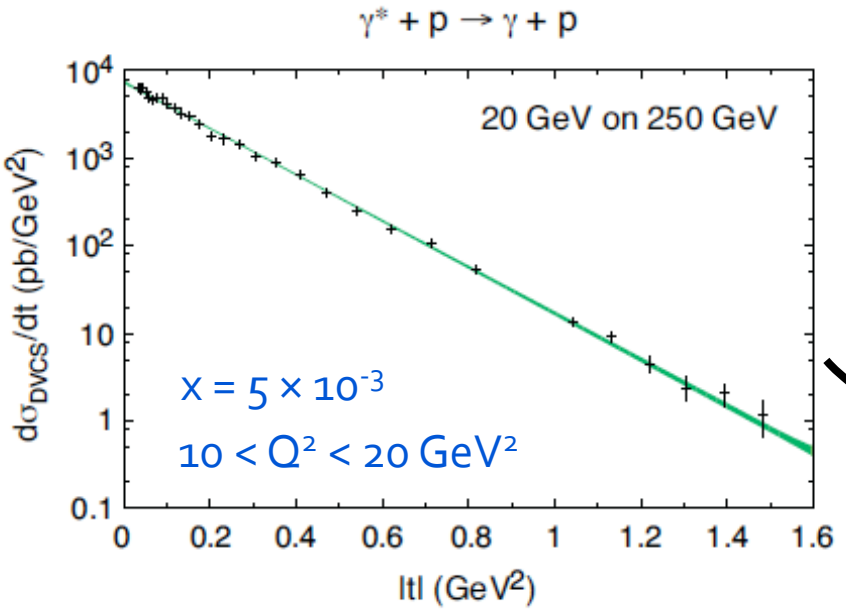
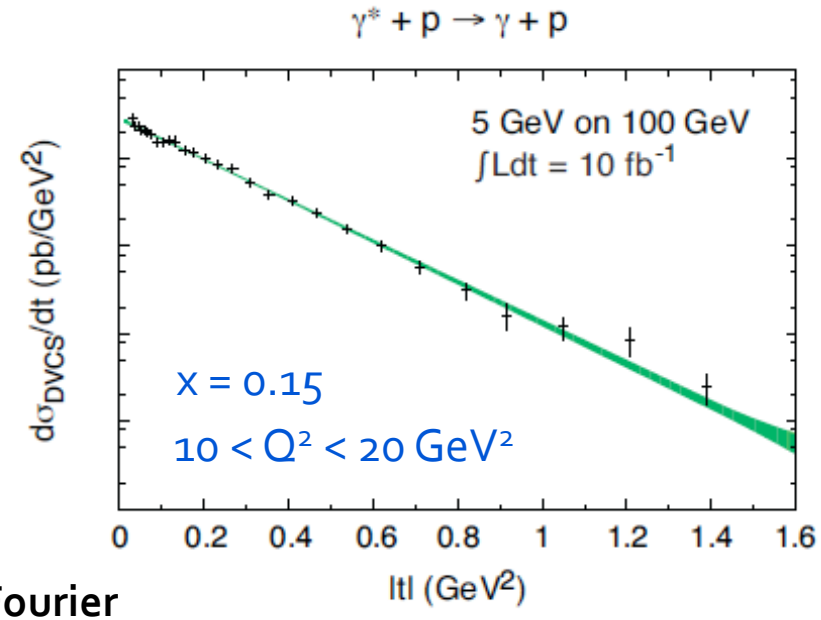
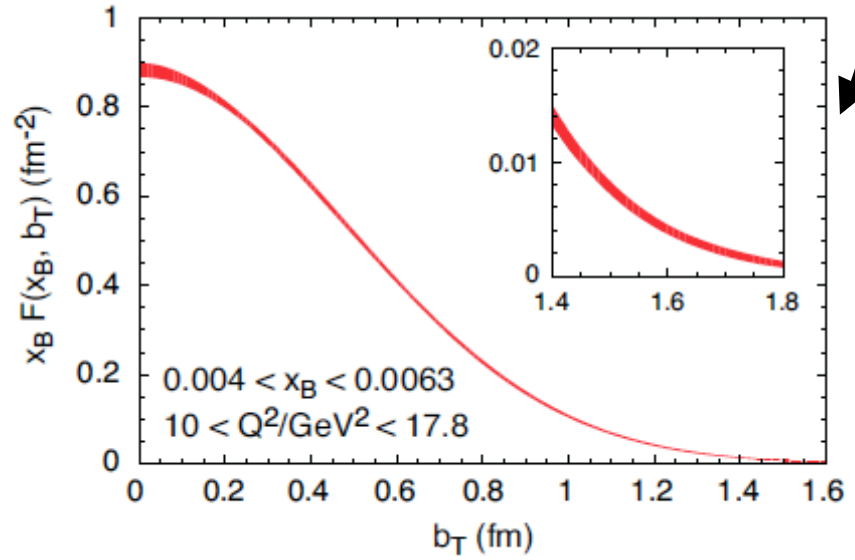
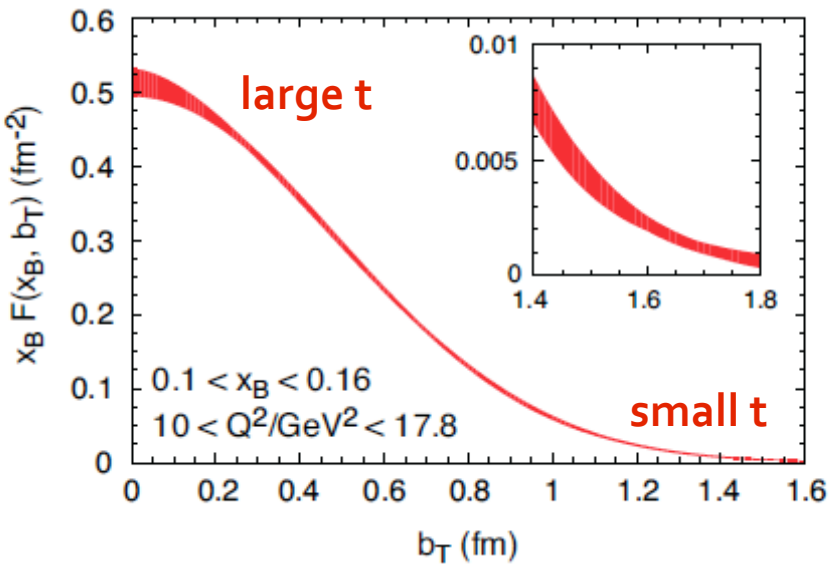




Fourier





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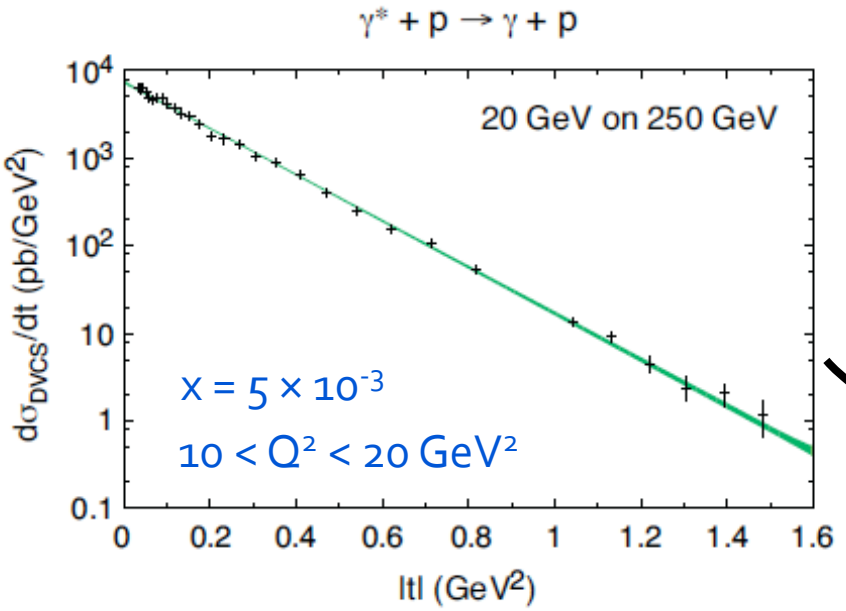

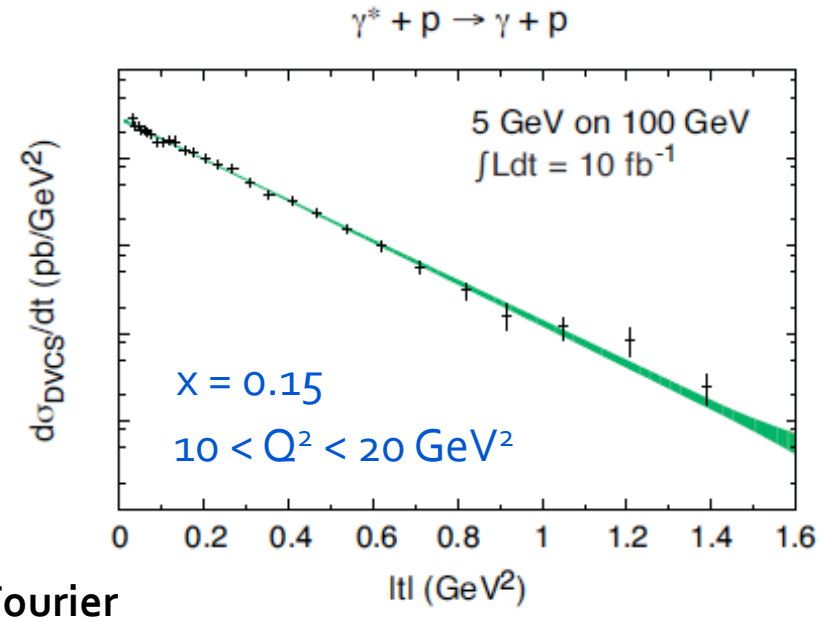

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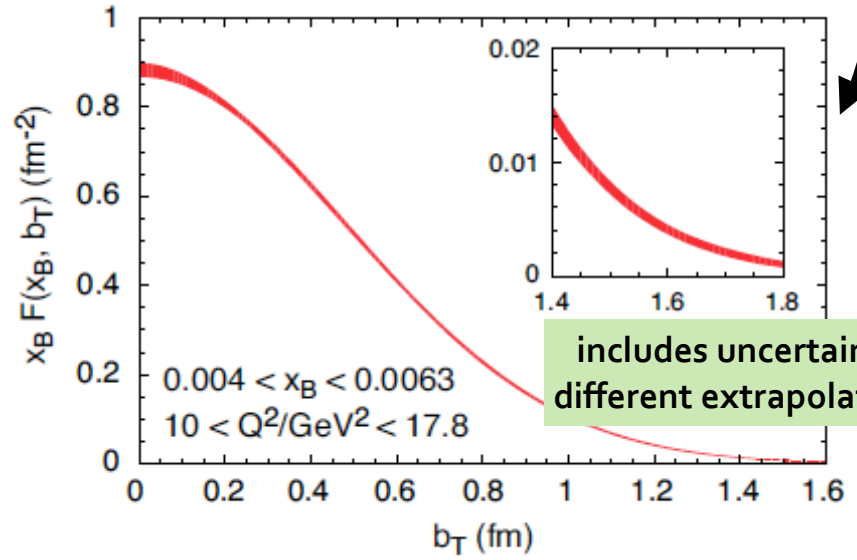
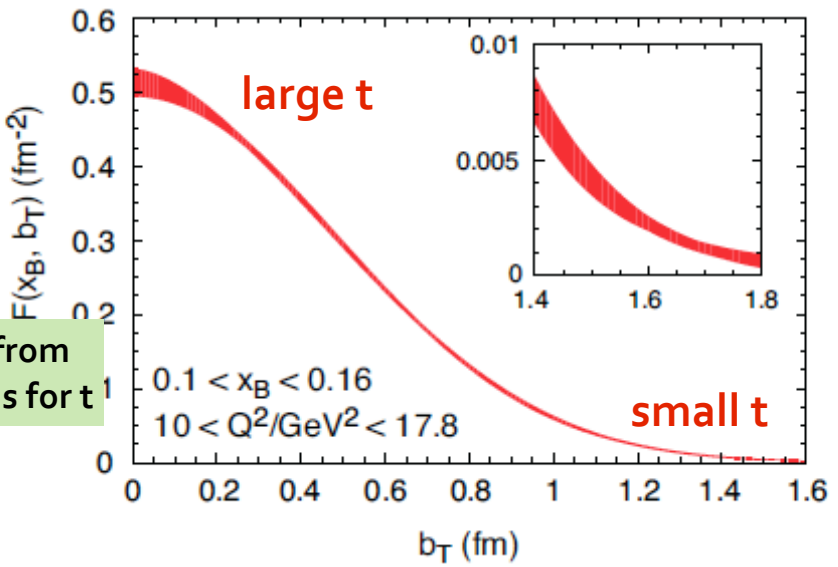


includes uncertainty from different extrapolations for t



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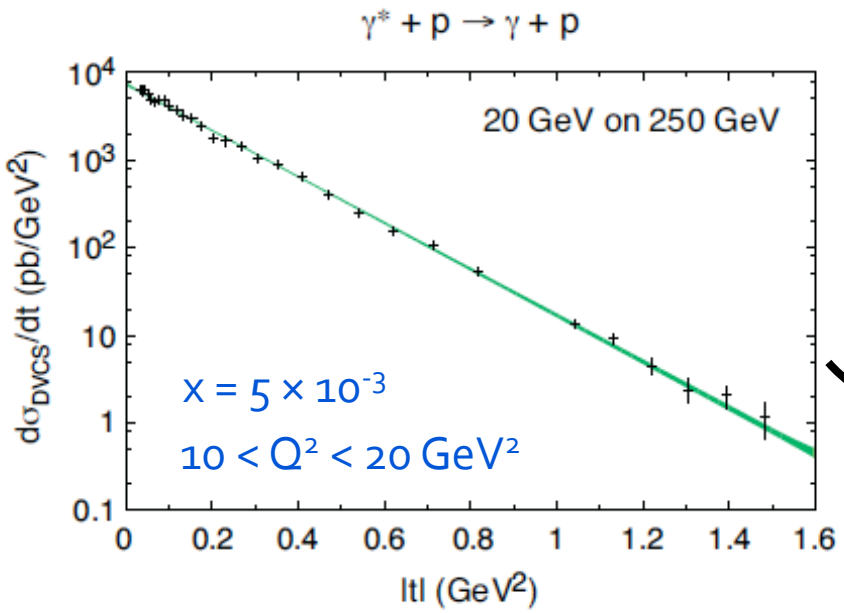

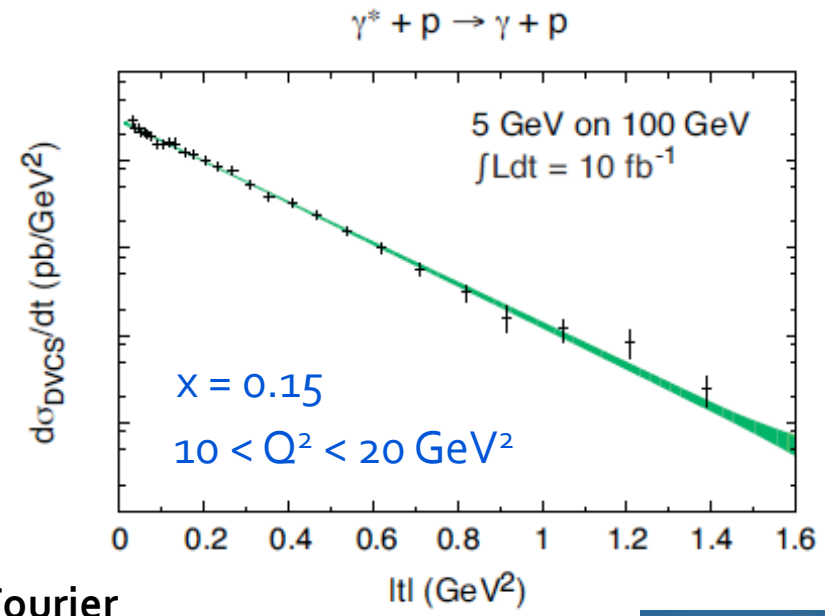

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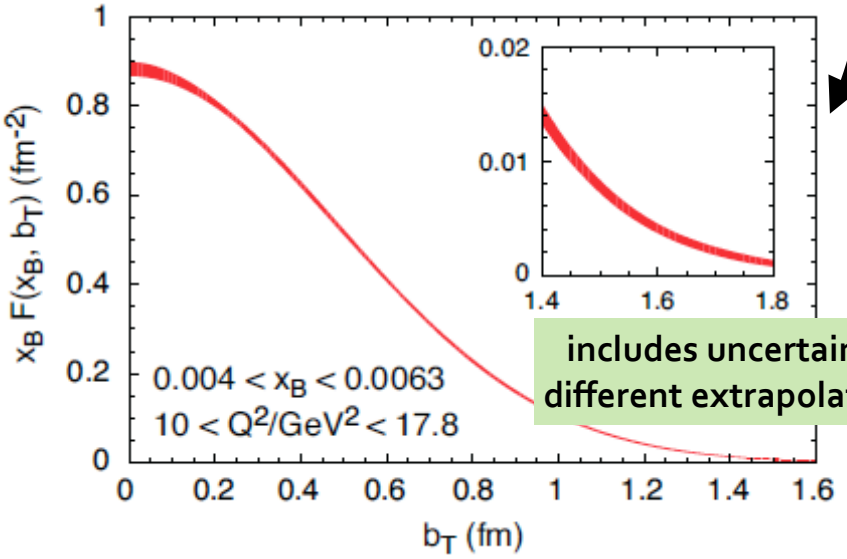

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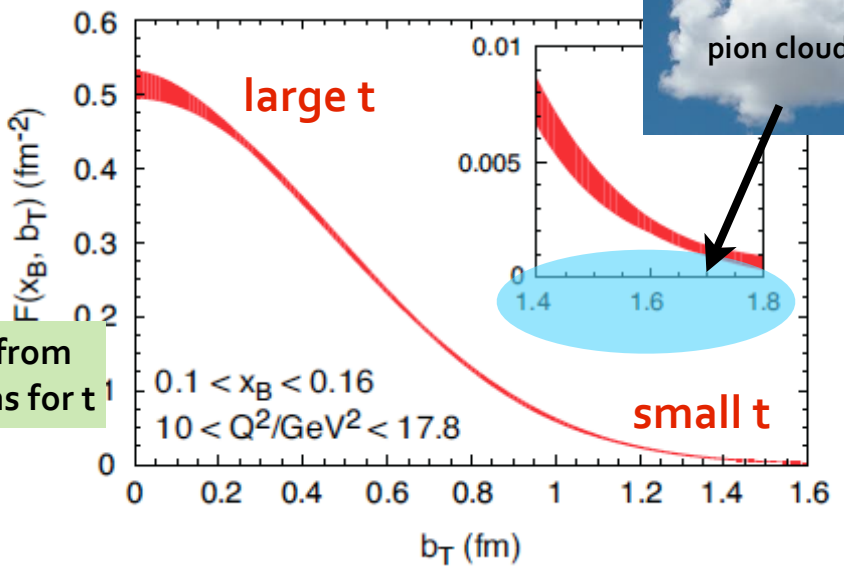
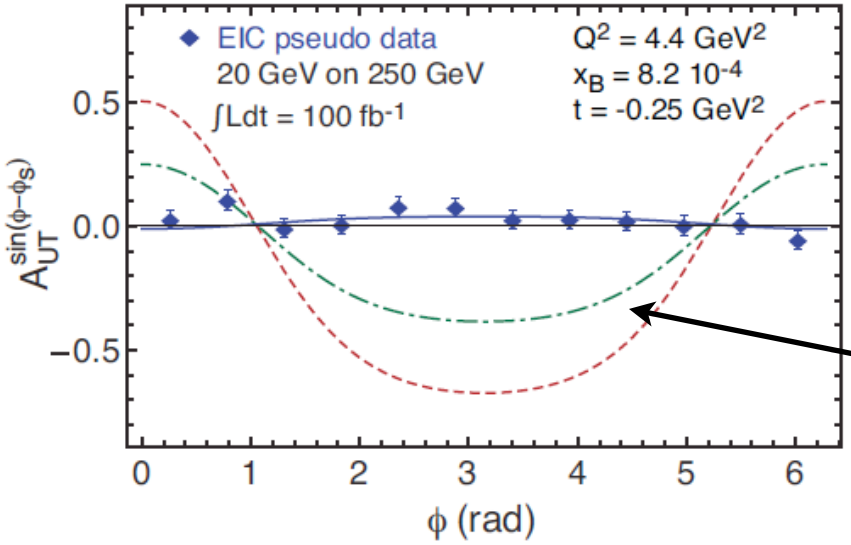


DVCS - what can we learn?



- unpolarized DVCS mainly sensitive to GPD H
- unknown GPD E from angular asymmetries with transversely polarized protons

different assumptions for GPD E

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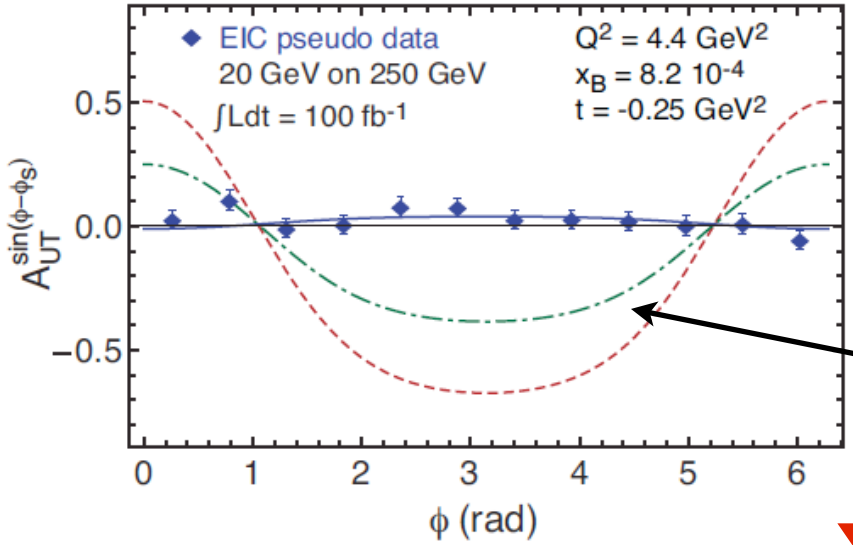

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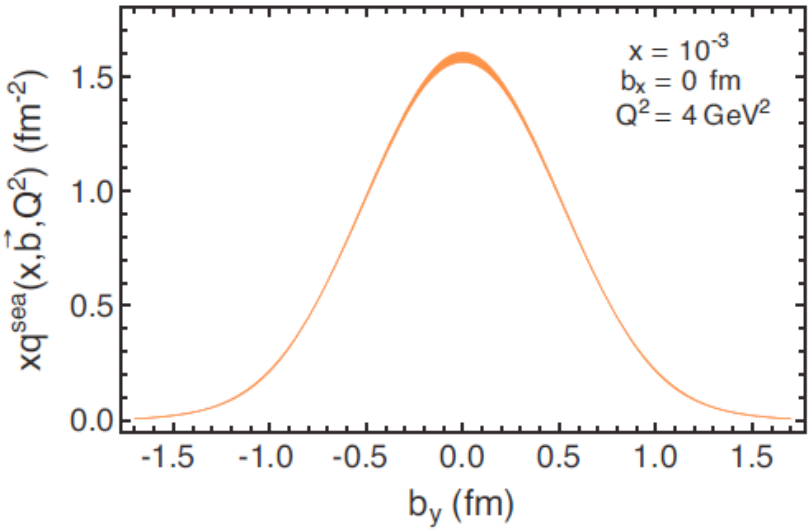
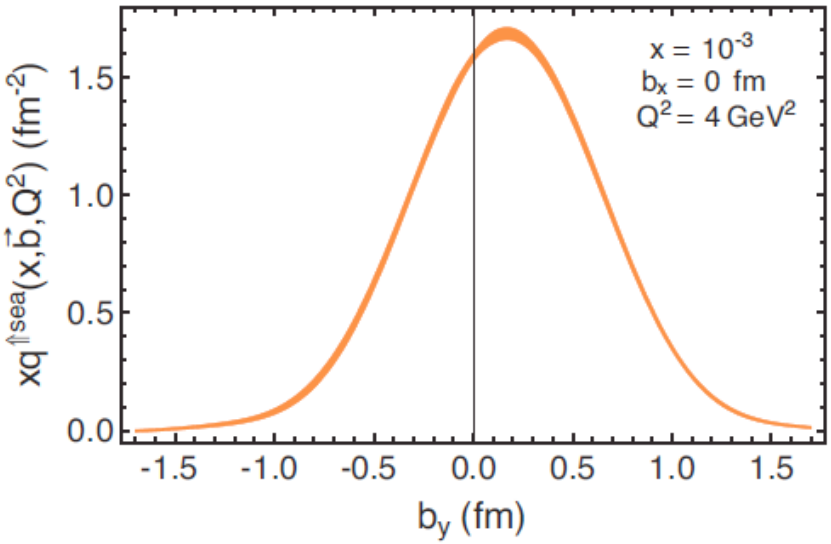
global QCD fits to data & Fourier transform to b space

quarks (unpolarized proton)



quarks (transversely pol. proton)



DVCS - what can we learn? - cont'd

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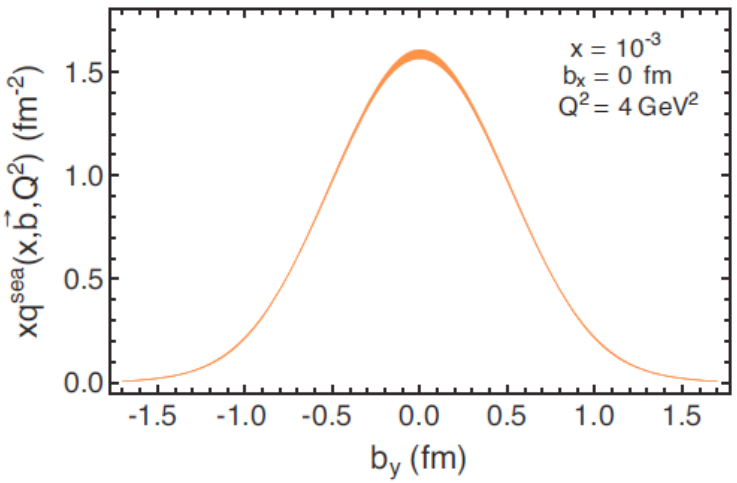

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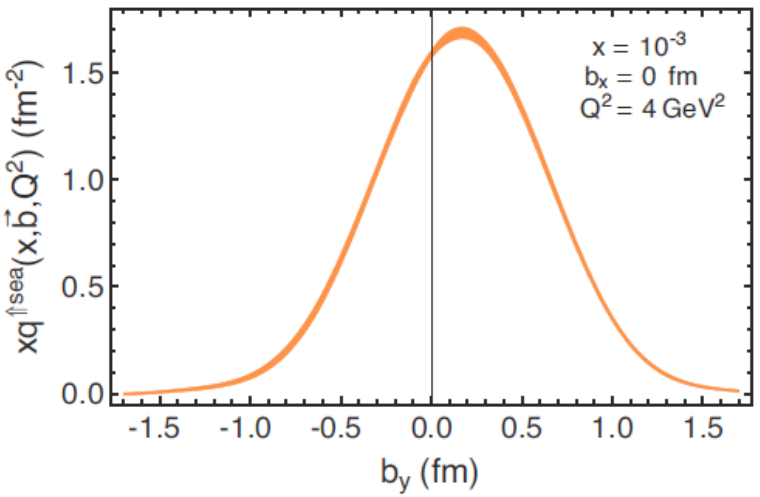
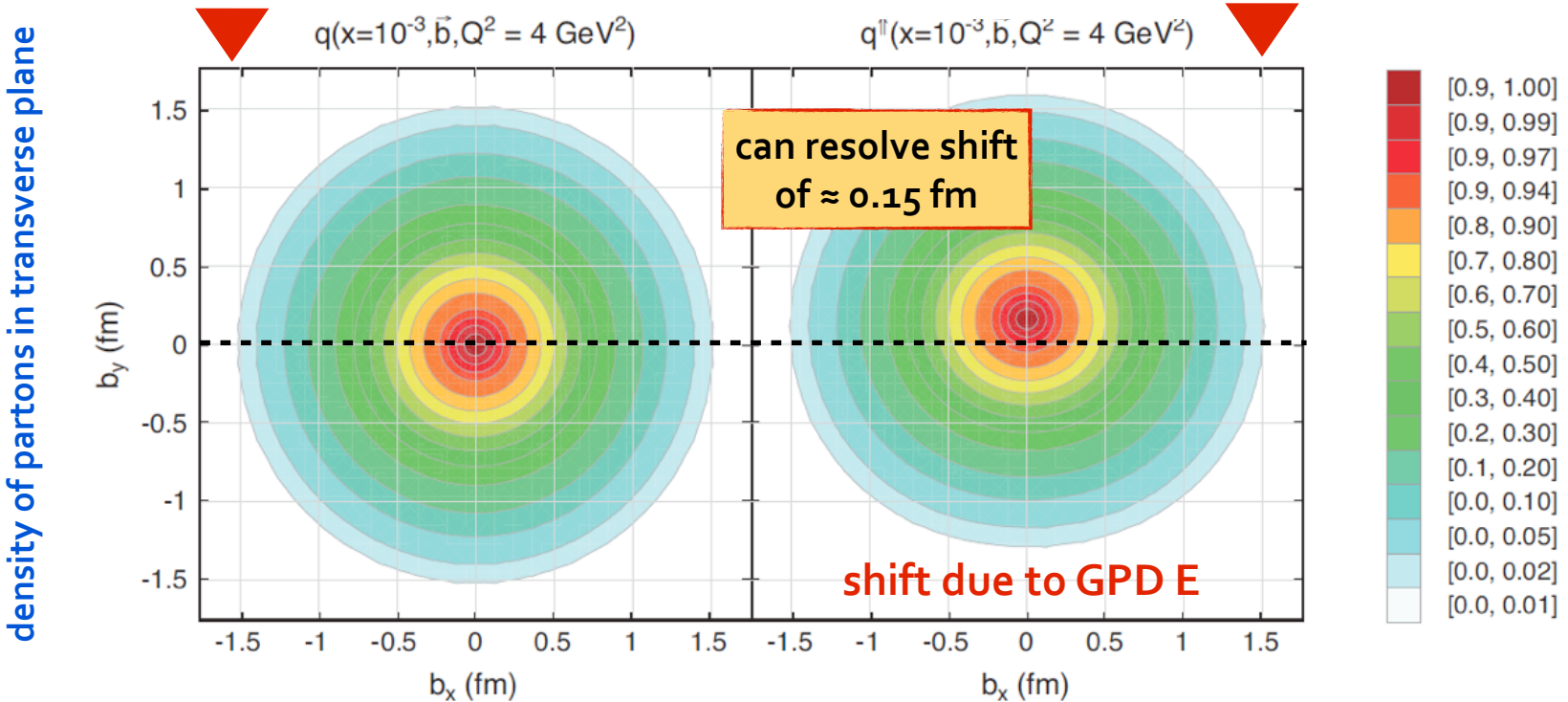


density of partons in transverse plane



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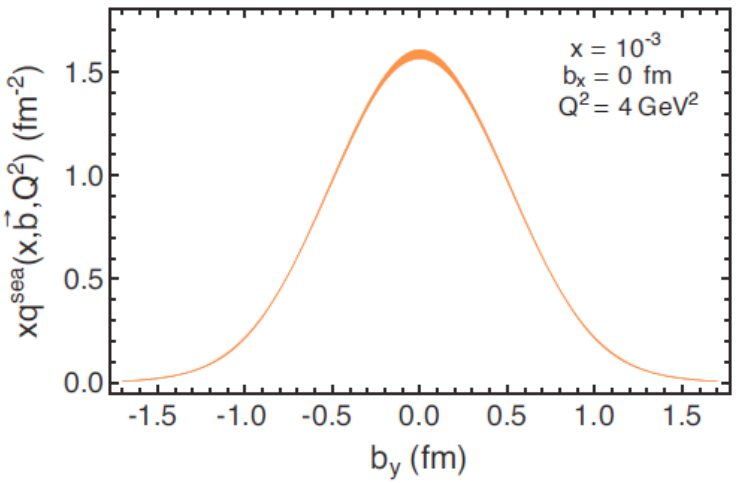

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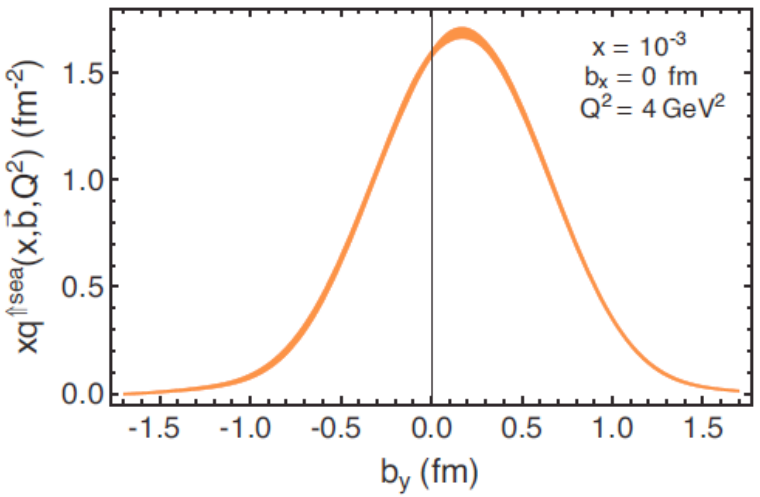

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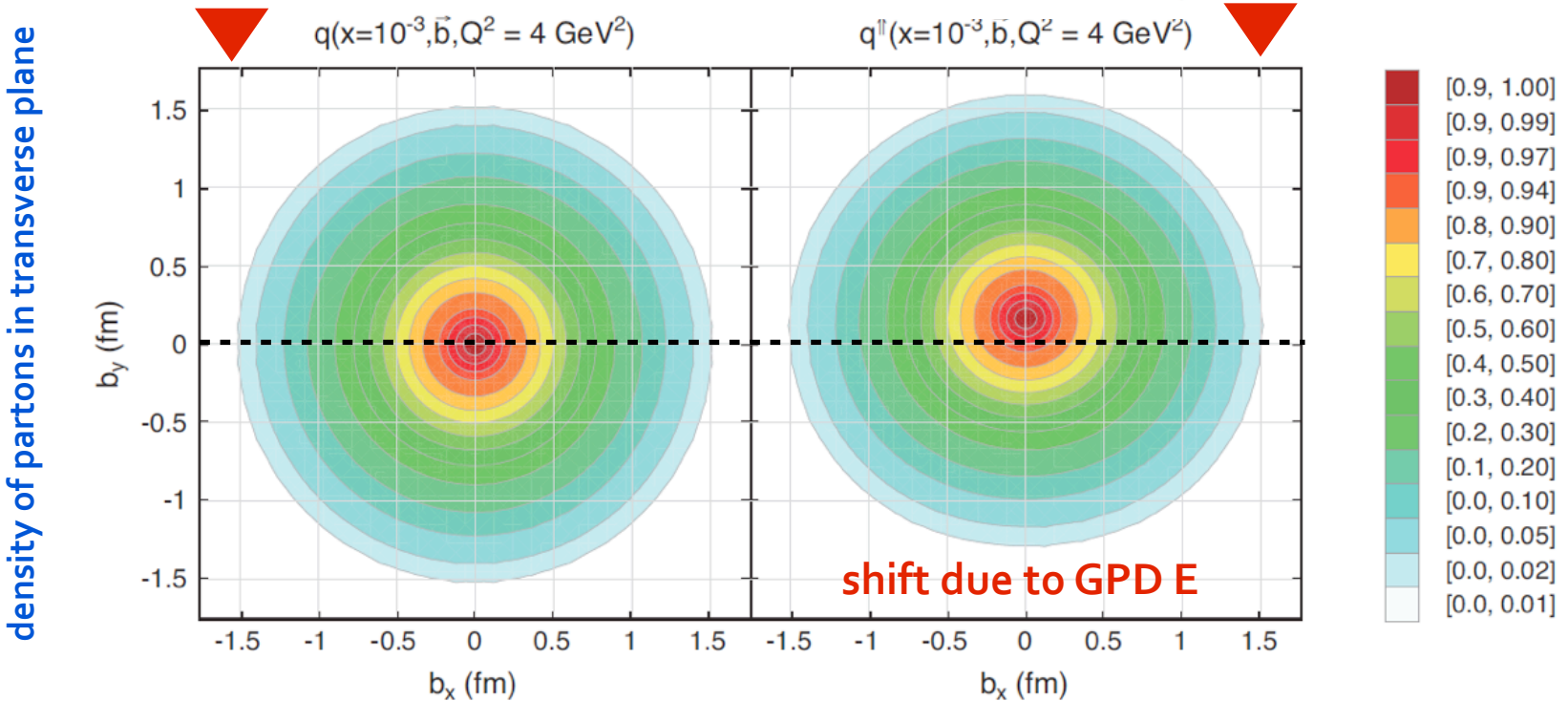

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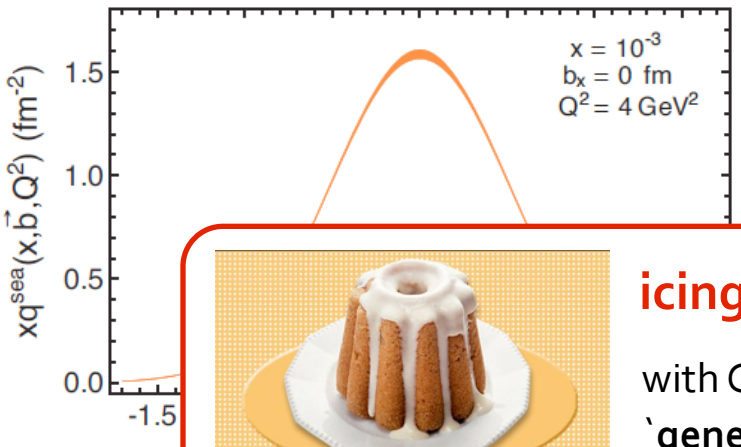

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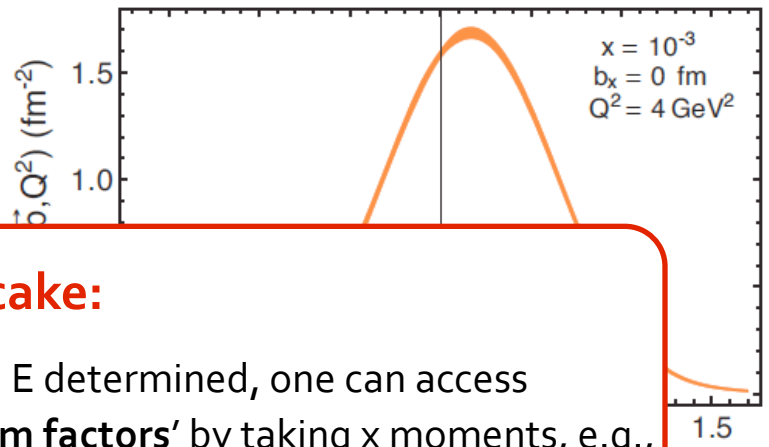


icing on the cake:

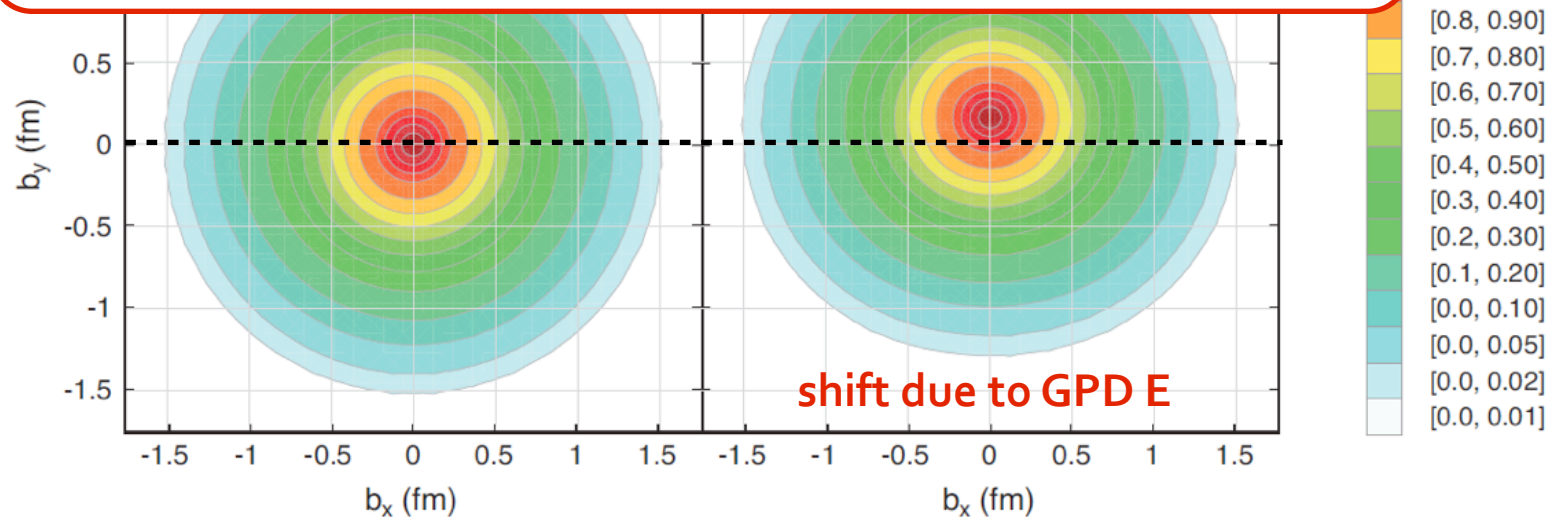
with GPDs H and E determined, one can access '**generalized form factors**' by taking x moments, e.g.,

Ji's sum rule

$$\mathbf{J_{q,g}} = \frac{\mathbf{1}}{\mathbf{2}} \int \mathbf{dx\, x} \left[\mathbf{H^{q,g}(x,\xi,t \to 0) + E^{q,g}(x,\xi,t \to 0)} \right]$$

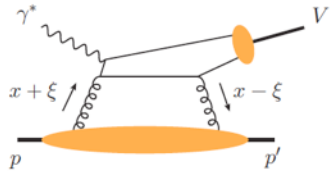
total angular momentum of quarks and gluons

density of partons in transverse plane



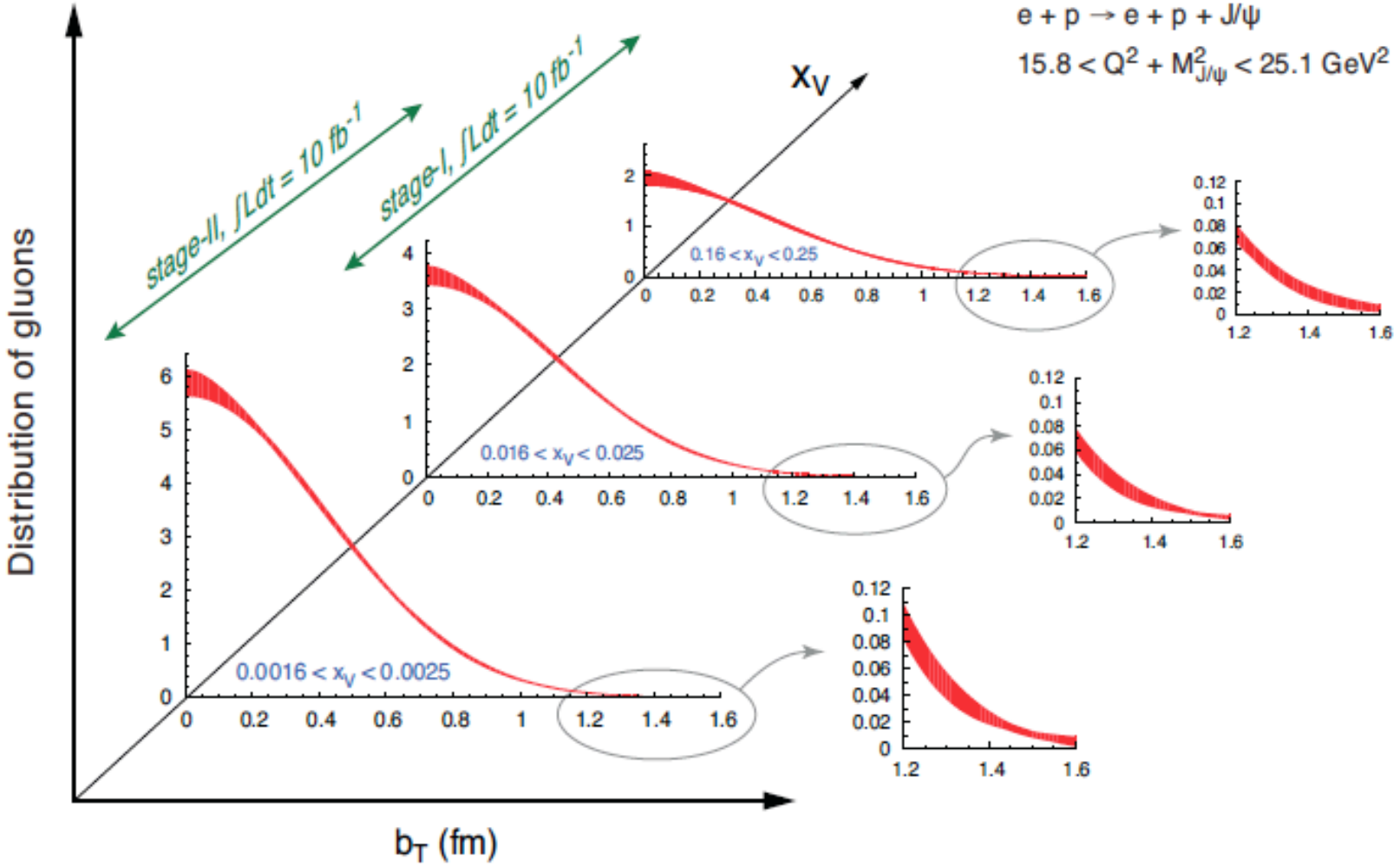
gluon imaging through J/Ψ production

- DVCS permits determination of gluon GPD through Q^2 evolution (similar to DIS)
- can be further improved by adding vector meson observables



$e + p \rightarrow e + p + J/\psi$

$15.8 < Q^2 + M^2_{J/\psi} < 25.1\ GeV^2$



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requirements

- large enough c.m.s. energy to explore small x region
- sufficient luminosity for multi-dimensional binning, ...
- sufficient control of systematic uncertainties
- state-of-the-art detector systems, well integrated into IR

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precisi… TMDs, and GPDs … comprehensive … the nucleon ever: … spin, and spatial structure

entire science program uniquely tied to a future high-energy electron-ion collider

never been measured before & never without

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